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Name and Address of Patentee:

Wake Forest University, Office Of Research Develop. Medical Center Boulevard Winston-Salem NC 27157-1023 United States Of America

Name of Actual Inventor: David J Vining

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(71) Applicant(s)

Wake Forest University

(72) Inventor(s)

David J Vining

(74) Agent/Attorney

DAVIES COLLISON CAVE,GPO Box 3876,SYDNEY NSW 2001

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METHOD AND SYSTEM FOR PRODUCING INTERACTIVE,
THREE-DIMENSIONAL RENDERINGS OF SELECTED BODY
ORGANS HAVING HOLLOW LUMENS TO ENABLE SIMULATED
MOVEMENT THROUGH THE LUMEN

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Background of the Invention

For many forms of cancer, early detection is essential for a favorable prognosis. The cancerous growth must be detected at an early stage before the 10 cancer is allowed to grow and spread. Such is the case for colorectal and lung cancers. As a result, techniques have been developed to examine the colon and tracheobronchial airways for the growth of precancerous and cancerous masses.

15 Colon cancer is the second leading cause of cancer death in the United States today. Fortunately, most colorectal carcinomas arise from preexisting adenomatous polyps, and the risk of cancer is directly related to the size of the polyp (1% in polyps less than 1 cm, 10% in polyps between 1 and 2 cm, and 30% in polyps 2 cm or greater). Scientific studies suggest that the early detection and removal of small carcinomas and precursor adenomatous polyps reduces mortality. Therefore, current strategies for colon 20 cancer screening focus on the early discovery of polyps. The techniques used to screen for colorectal cancer include flexible sigmoidoscopy (the use of a fiberoptic scope to examine the distal half of the colon) and fecal occult blood testing (wherein 25 hemorrhage is detected). There is some debate on the effectiveness of colorectal cancer screening, but it 30

has been predicted that a 30-40% reduction in mortality can be achieved with proper screening using a combination of fecal occult blood testing and sigmoidoscopy.

5 The National Cancer Institute and the American Cancer Society recommend colorectal cancer screening for persons of average risk who are more than 50 years old using sigmoidoscopy and annual fecal occult blood tests. The fecal occult blood test is
10 easy to perform but is plagued by many false positive and false negative results. Sigmoidoscopy suffers from the fact that it only examines the distal half of the colon (the rectum and the sigmoid colon). This is a serious shortcoming since approximately 40% of
15 colorectal carcinomas occur proximal to the splenic flexure and are therefore undetectable using sigmoidoscopy.

Examination of the entire colon by a barium enema or conventional colonoscopy increases
20 sensitivity for cancer detection but also increases the risks and costs. A barium enema causes patient discomfort and/or embarrassment and exposes the patient to substantial radiation. Colonoscopy, like sigmoidoscopy, does not always examine the entire
25 colon since the cecum is not reached in approximately 15% of colonoscopies. In addition, colonoscopy requires patient sedation, places the patient at risk for bowel perforation, and is comparatively expensive. Furthermore, with the exception of fecal occult blood
30 testing, all of these procedures meet with significant patient discomfort.

Turning now to the tracheobronchial examination, Transbronchial Needle Aspiration (TBNA) is a bronchoscopy technique that permits the outpatient diagnosis and staging of mediastinal disease. This procedure allows for the outpatient sampling of tissue specimens that might otherwise require a surgical procedure. With TBNA, a needle is placed through an airway wall in the vicinity of a suspected lesion to retrieve a tissue sample.

Conventionally, the bronchoscopist is guided only by a mental model of the patient's anatomy and pathology following review of bronchoscopy images and/or a series of thoracic computed tomography (CT) images. As can be expected, proper placement of the needle can be extremely difficult and to a small degree somewhat imprecise.

Accordingly, it is highly desirable to have a reliable, efficient method for examining the tracheobronchial tree and/or the colon of a patient to detect early cancer. The technique should allow for the discovery of polyps of 1 cm or greater in size in the colon and 5 mm or greater in the airways. Preferably, the method should reduce the amount of discomfort encountered by the patient, decrease the risk of injury to the patient, and be conducted in a reasonable amount of time without being prohibitively expensive. Preferably, the method should be non-invasive or minimally invasive.

Summary of the Invention

In accordance with the present invention, a system and method are provided for producing two-dimensional images of a selected structure, such as a

portion of the body, to enable the creation of a three-dimensional rendering of the selected structure. More specifically, two-dimensional images of a selected body portion are acquired with use of a 5 scanner, for example, a helical computed tomography (CT) scanner. The two-dimensional images are then stacked to create a three-dimensional image volume. From the three-dimensional volume, image features of one or more selected body organs are isolated or 10 segmented. Isosurfaces of the segmented organs are produced and wireframe models are then generated from each of the isosurfaces for the respective segmented organs. The wireframe models are used to generate real time, three-dimensional images (renderings) of 15 the selected organs.

In a specific application for generating a three-dimensional rendering of a patient's colon, the patient initially undergoes a selected preparation procedure. For example, the patient's colon is 20 initially cleansed and then inflated with air to permit the acquisition of unobstructed two-dimensional images of the colon. Next, the patient undergoes a CT scan to produce a series of two-dimensional images of the patient's internal organs. Preferably, a spiral 25 or helical CT scanner is employed to provide a series of uninterrupted two-dimensional images through the body. The series of two-dimensional images are transferred from the scanner to a graphics computer to effect various image processing procedures. The 30 dataset corresponding to the series of two-dimensional images may be transferred to the graphics computer in a compressed format for decompression on the graphics computer. Alternatively, the dataset representing the series of two-dimensional images may be decompressed

on the computer console of the scanner prior to transfer to the graphics computer.

After transfer to the graphics computer, the series of two-dimensional images are stacked in order 5 to form a three-dimensional volume file. In order to facilitate three-dimensional rendering of a selected organ contained within the three-dimensional volume of images, the three-dimensional volume file may be subjected to various optional dataset reduction 10 techniques. For example, a reduction of pixel resolution on the series of two-dimensional images may be effected. In addition, the three-dimensional volume file may be separated into selected subvolumes.

After the optional dataset reduction 15 procedure is completed, an image segmentation process is performed in order to isolate features of a selected organ or region of interest from the three-dimensional volume file. Image segmentation may be effected by various techniques. For example, an image 20 slice through the three-dimensional volume file may be subjected to a thresholding process in which a physical property of the two-dimensional image slice, such as x-ray attenuation, may be used to establish a particular threshold range, such as a range of x-ray 25 attenuation values, that corresponds to the organ of interest. After an appropriate threshold range is determined, the entire three-dimensional volume file is then thresholded to segment the organ of interest. For example, in order to segment the colon, a 30 threshold range corresponding to the air column within the colon could be selected to isolate the inner wall of the colon.

- An alternative segmentation technique may be employed in which a region growing technique is used to isolate the air column within the colon. Using the region growing technique, a "seed" is planted by
- 5 selecting a data point or voxel within the air column of the colon. Neighboring voxels are progressively tested for compliance with a selected acceptance criteria, such as x-ray attenuation values falling within a selected threshold range representing air.
- 10 As such, the seed region continues to expand or grow until the entire air column within the lumen of the colon is filled.

A surface, or isosurface, of the air column representing the colon is then produced. A wireframe model of the isosurface is then generated using a selected image processing technique such as a marching cubes algorithm. From the wireframe model of the colon, a three-dimensional interactive rendering is produced that enables the user to rapidly view a

15 series of three-dimensional images of the lumen of the colon for purpose of detection of pathological conditions. As such, a user has the perception of flying through the lumen and virtual reality environment is achieved.

25 Other procedures may be employed with the interactive, three-dimensional rendering of the organ for purposes of medical diagnosis or observation. For example, a three-dimensional rendering of the colon may be split open so that the interior half of the

30 colon along a selected length may be viewed. In addition, selected flights or paths of movement through the lumen of the colon may be recorded on videotape or, alternatively, stored in the memory of

the graphics computer as a path of coordinates for subsequent reproduction and display. In addition, various areas of pathology may be marked by different colors during a flight through the lumen of the colon
5 to facilitate subsequent detection.

The method and system of the present invention may also be used to isolate other organs. For example, the system and method may be used to isolate the tracheobronchial airways, as well as the
10 surrounding lymph nodes and blood vessels. During an interactive, three-dimensional rendering, a selected organ may be rendered transparent to facilitate or permit a view of the remaining (surrounding/neighboring) organs. For example, the
15 airway walls may be made transparent so that the surrounding blood vessels and lymph nodes become visible from a perspective within the interior of the airways.

Brief Description of the Drawings

20 The foregoing summary, as well as the following detailed description of the preferred embodiments of the present invention, will be better understood when read in conjunction with the accompanying drawings, in which:

25 Fig. 1 is a flowchart representing a method in accordance with the present invention of producing interactive, three-dimensional renderings of selected structures such as a selected body organ;

30 Fig. 2 is a flowchart representing a general process in accordance with the present invention of

converting two-dimensional images of a selected body organ into a three-dimensional image;

Fig. 3 is a block diagram of a system used in the method of the present invention;

5 Fig. 4 is a flowchart representing the steps involved in a data reduction process used in the method of the present invention;

10 Fig. 5 is a flowchart representing the steps involved in segmentation of an image of the selected body organ from a three-dimensional volume;

Fig. 6 is a flowchart representing the steps involved in a region growing procedure for segmentation of an image of the selected body organ from a three-dimensional volume;

15 Fig. 7 is a perspective view of a three-dimensional rendering showing the selection of coordinates X_{\min} , X_{\max} , Y_{\min} , Y_{\max} , Z_{\min} , and Z_{\max} to define a selected subvolume containing a colon;

20 Fig. 8 is a view of a thresholded two-dimensional image slice of a colon displayed together with the corresponding gray-scale image;

Fig. 9 is a representation of a wireframe model of a selected portion of the colon;

25 Fig. 10 is a three-dimensional rendering of the portion of the colon represented by the wireframe model shown in Fig. 9;

Fig. 11 is an external perspective view of a three-dimensional rendering of a selected portion of the colon;

5 Fig. 12 is a split-open view of the selected portion of the colon shown in Fig. 11;

Fig. 13 is a map view showing a three-dimensional rendering of the colon on which a location marker is superimposed on the image;

10 Fig. 14 is a three-dimensional rendering of a selected section of the colon corresponding to the location of the marker shown in Fig. 13;

15 Fig. 15 is a perspective view of a three-dimensional rendering showing the selection of coordinates X_{\min} , X_{\max} , Y_{\min} , Y_{\max} , Z_{\min} , and Z_{\max} to define a selected subvolume containing a tracheobronchial tree;

20 Fig. 16 is a view of a thresholded two-dimensional image slice of a tracheobronchial tree displayed together with the corresponding gray-scale image;

Fig. 17 is a representation of a wireframe model of a selected portion of the tracheobronchial tree;

25 Fig. 18 is a three-dimensional rendering of the portion of the tracheobronchial tree represented by the wireframe model shown in Fig. 17;

Fig. 19 is an external perspective view of a three-dimensional rendering of a selected portion of the tracheobronchial tree;

5 Fig. 20 is a split-open view of the selected portion of the tracheobronchial tree shown in Fig. 19;

Fig. 21 is a map view showing a three-dimensional rendering of the tracheobronchial tree on which a location marker is superimposed on the image;

10 Fig. 22 is a three-dimensional rendering of a selected section of the tracheobronchial tree corresponding to the location of the marker shown in Fig. 21;

Fig. 23 is a diagrammatic view depicting a model for determining a center line through a lumen;

15 Fig. 24 is a flowchart representing a procedure for making a three-dimensional rendering of a selected organ transparent relative to three-dimensional renderings of remaining organs;

20 Fig. 25 is a flowchart representing a procedure for establishing "go to" points at selected locations on a three-dimensional rendering to cause the display of a three-dimensional rendering of the specific location selected by a respective "go to" point;

25 Fig. 26 is a diagram depicting a pick point procedure in which a selected pick point on a three-dimensional image causes the display of three orthogonal planes passing through the pick point; and

Fig. 27 is a flowchart showing the steps involved in morphological dilation.

Detailed Description of the Preferred Embodiments

The present invention generally relates to a method and system, as schematically represented in Figs. 1, 2, and 3, for generating and displaying interactive, three-dimensional structures. The three-dimensional structures are in the general form of selected regions of the body and, in particular, body organs with hollow lumens such as colons, tracheobronchial airways, blood vessels, and the like. In accordance with the method and system of the present invention, interactive, three-dimensional renderings of a selected body organ are generated from a series of acquired two-dimensional images.

As illustrated in Fig. 3, a scanner 22, such as a spiral or helical CT (Computed Tomography) scanner, operated by a computer console 24 is used to scan a selected three-dimensional structure, such as a selected anatomy, thereby generating a series of two-dimensional images 12 through that structure. A general procedure for converting or transforming the set of two-dimensional images 12 of the structure into a three-dimensional rendered image 17 is schematically illustrated in Fig. 2. Any type of digital image (CT, MR, US, SPECT, PET) is amendable to three-dimensional image processing. However, the acquisition of contiguous thin slices is imperative for generating acceptable three-dimensional images. Recent developments of volume acquisition devices such as spiral/helical CT, three-dimensional MRI, and three-

dimensional ultrasound equipment make it feasible to render three-dimensional images of any organ system.

Referring to Fig. 2, each of the individual two-dimensional images 12 defines a two-dimensional (X-Y) matrix of picture elements, or pixels, with each pixel representing a predetermined physical property associated with the three-dimensional structure or organ at a particular location within the three-dimensional structure. Successive two-dimensional images 12 are spaced in a third-dimensional direction (Z) throughout the three-dimensional structure. The two-dimensional images 12 are typically obtained from a helical computed tomography (CT) scanner 22 operated by a computer console 24. For example, the scanner 5 may be a General Electric HiSpeed Advantage Helical CT Scanner connected with an optional General Electric Independent computer console or physician's console. The computer console 24 may, however, be an integral 10 part of the helical CT scanner 22 instead of a separate independent console. The two-dimensional images 12 can also be obtained from ultrasound, positron emission tomography, emission computed 15 tomography, and magnetic resonance imaging. The physical property measured is directly associated with the scanning technique used to produce the two-dimensional images 12. For CT images the physical 20 property measured is x-ray attenuation, while for magnetic resonance images (MRI) the physical property measured is related to various properties such as 25 proton density.

As shown in Fig. 2, the series of two-dimensional images 12 is stacked to form a three-dimensional volume 13, thereby defining a three-

dimensional matrix (X, Y, Z axes) that represents at least one physical property associated with the three-dimensional structure at coordinates positioned throughout the three-dimensional volume. The three-
5 dimensional matrix is composed of three-dimensional volume elements, or voxels, which are analogous to two-dimensional pixels. From the three-dimensional volume 13, a targeted volume 14 is selected for three-dimensional rendering. For example, the targeted
10 volume 14 may include a selected organ or region of interest that is to be isolated from the original three-dimensional volume 13. The targeted volume 14 may include an entire organ or, alternatively, may include an air column or volume confined within an
15 organ or a lumen of the organ.

A dataset representing the original three-dimensional volume 13 may be optionally subjected to a dataset reduction process to decrease image or spatial resolution or to divide the original volume into
20 smaller subvolumes of data prior to isolating the targeted volume 14. Dataset reduction and/or subvolume selection are only necessary if the capabilities of the graphics computer 26 are inadequate to process the full three-dimensional
25 volume 13 for effective or efficient three-dimensional rendering. In order to obtain three-dimensional constructions 17 in real time, it may be necessary to reduce the size of the dataset representing the three-dimensional volume 13 of images. For example, the
30 dataset of the original three-dimensional volume 13 may need to be reduced from an original size of 100-250 Megabytes to a reduced size of about 5-10 Megabytes. However, the amount of reduction, if any, may vary depending upon the size of the original

dataset and the processing speed and capability of the graphics computer 26 used for three-dimensional rendering.

5 An optional dataset reduction process 65 is generally represented in Fig. 4. When necessary, dataset reduction can be accomplished by reducing the pixel resolution, for example, from 16 bits per pixel to 8 bits per pixel. The reduction in pixel resolution, represented by step 67 in Fig. 4,

10 decreases the image contrast in the final displayed three-dimensional images by reducing the number of shades of gray from 2^{16} to 2^8 . While not preferable in particular applications, dataset reduction may also be effected by decreasing spatial resolution, as

15 represented by step 69 in Fig. 4. For example, each two-dimensional image 12 stored on a matrix of 512 pixels x 512 pixels may be reduced to a matrix of 256 pixels x 256 pixels through spatial manipulation of information.

20 Further reduction of the dataset size of the original three-dimensional volume 13 can be effected, if necessary, by selecting a subvolume of the dataset to be displayed, as represented by step 68 of Fig. 4. For example, the colon can be subdivided into the

25 rectum, the sigmoid colon, the descending colon, the splenic flexure, the transverse colon, the hepatic flexure, the ascending colon, and the cecum. A separate subvolume may then be created for one or more of such subdivisions of the colon.

30 Following dataset reduction, the three-dimensional image of the organ or region of interest is segmented (isolated) from the volume of data. A

range of tissue values, which depends on the physical property measured (e.g., x-ray attenuation), may be selected to designate the organ or region of interest. The organ or region of interest is then isolated from
5 the volume of data. A general method or process 70 for segmenting an image of a selected organ or region of interest is represented in Fig. 5. The region of interest may, for example, be the air column comprising the colon or tracheobronchial airways, or
10 some other body part having a lumen filled with a homogeneous substance (i.e., air, blood, urine, etc.). Alternatively, the region of interest may be a section of bone.

The segmentation process 70 may be effected,
15 for example, by designating a range of physical property values bounded by threshold limits that function to designate the organ of interest. For the selected volume or subvolume, voxels falling within a selected thresholding range are assigned a single value, for example, 255 to provide a white color, whereas voxels falling outside of the selected thresholding range are assigned a different single value, for example, 0 to provide a black color. Accordingly, the selected volume is thresholded by
20 comparing each voxel in the selected volume to the threshold limits and by assigning the appropriate color value 0 or 255 to each such voxel depending on whether each such voxel falls inside or outside the threshold range defined by the threshold limits. By
25 thresholding the selected volume, the target volume 14 is formed having equal voxel values. More specifically, a target organ 14 is produced having a white color while all volumes outside the threshold limits are produced having a black color. With the
30

exception of various artifacts, which can be eliminated using image-processing techniques, only the thresholded target organ 14 is colored white and everything else is colored black.

5 From the thresholded target volume 14, an isosurface 15 is defined. The isosurface 15 is an exterior surface of equal voxel value on the thresholded target volume 14 which is established by the selected thresholding range.

10 A wireframe model 16 is generated from the isosurface 15. The wireframe model 16 is formed as a series of polygonal surfaces that approximates the surface of the region of interest such as the selected organ. The wireframe model 16 is defined by a series
15 of vertices which are interconnected by a set of line segments. The wireframe model 16 appears as a three-dimensional wire mesh object which can be rendered into a three-dimensional image 17. The three-dimensional image 17 is generated by appropriately shading the polygons of the wireframe model 16 to provide a three-dimensional image of the selected organ. The three-dimensional image 17 is displayed on a computer monitor 28. Additionally, the displayed imagery 17 can be recorded on a video recorder 30 or
20 photographed for future viewing. An input, in the form of a computer mouse 27, is provided on the graphics computer 26 to permit a user to manipulate the displayed imagery.

25 The method of the present invention can be used to display a colon in three dimensions and, in a more specific application, to enable real-time or interactive three-dimensional rendering of the colon

which thereby enables user interaction with the colon imagery, i.e. virtual reality. While user interaction with the three-dimensional images of the colon is simulated, the three-dimensional image itself is an
5 accurate, three-dimensional view of the actual colon.

A method for generating interactive, three-dimensional renderings of a patient's colon in accordance with the present invention is generally set forth in Fig. 1. At step 40, a patient is initially
10 prepared for imaging by cleansing the patient's colon. The cleansing procedure can be accomplished with a clear liquid diet in conjunction with laxatives. Alternatively, a Golytely prep can be administered on the day before the exam. The purpose of the cleansing
15 procedure is to eliminate feces from the colon. Optimally, an absolutely clean colon is desired prior to computed tomography (CT) scanning. Any retained feces or fluid can simulate or mask small polyps because it is sometimes difficult to differentiate
20 feces from the colon wall. The effectiveness of using a clear liquid diet or a Golytely prep procedure may still be somewhat hindered by small amounts of retained feces. As an alternative to cleansing the colon, or in conjunction with cleansing the colon, the
25 patient can be fed a low residue diet combined with a contrast agent (such as a low density barium, for example, 1.5% W/V barium) for about three days. Such a procedure may serve to homogeneously opacify any retained stool so that the image of the feces can then
30 be subtracted from the final display, or at least from selected images, using image processing techniques.

Once the colon has been cleansed, the colon is insufflated with gas to distend the colon.

- Distending the colon assures that the interior surface of the colon will be clearly visible in the final image display. A rectal catheter, i.e., a standard barium enema catheter (0.5 inch (1.27 cm) diameter is inserted and gas is introduced into the colon. The colon is filled to a predetermined pressure or volume by introducing the gas either as discrete puffs or at a constant flow rate. Although air can be used, CO₂ may be preferred since CO₂ passes through the colonic mucosa into the bloodstream and is subsequently exhaled, thereby decreasing the amount of bloating and cramping experienced by a patient after the examination. Unlike conventional colonoscopy, there is no need to sedate the patient for this procedure.
- After insufflation, the colon is then scanned, at step 45 of Fig. 1, by a helical CT scanner 22 to produce a series of two-dimensional images 12 of the colon. The picture elements, or pixels, in the images 12 represent at least one physical property associated with the colon. The physical property, for example, may be the x-ray attenuation of the colon wall or of the air column within the colon. The images 12 are generally taken at regularly spaced locations throughout the abdominal region of the patient. The smaller the spacing between successive images 12, the better the resolution in the final displayed imagery. Preferably, the spacing between successive images 12 is approximately 1mm to produce isocubic voxels since the X and Y dimensions are each approximately 1mm.

Immediately after inflating the colon, the abdomen is scanned, for example, with a GE HiSpeed Advantage Helical CT Scanner 22, during a single

breath-hold acquisition which is completed in about 30-50 seconds. The scanning parameters may consist of a 0.20 inch (5 mm) x-ray beam collimation, 0.4 inch/sec (10 mm/sec) table speed to provide 5 2:1 pitch, and a 0.04 inch (1 mm) image reconstruction interval. The x-ray beam collimation is the width of the x-ray beam which thereby establishes the CT slice thickness and Z-axis spatial resolution. The pitch is the CT table speed divided by the collimation. The 10 image reconstruction interval reflects the interval at which two-dimensional images are reconstructed. Using an x-ray beam collimation of 5mm and a selected reconstruction interval of 1mm, images reflecting a 5mm CT slice thickness are generated at 1mm intervals. 15 Consequently, there is an overlap of 4mm between successive 5mm thick images at a 1mm reconstruction interval.

A 50 second scan at a table speed of 10mm per second in a Z-axis direction creates a volume of 20 data having a Z-axis length of 500mm. Using a 1mm reconstruction interval over the length of the Z-axis of the volume of data produces 500 images with each image representing a 5mm thick section along the Z-axis. Consequently, up to 500 images may need to be 25 stored in compressed format on the CT scanner console or on a GE Independent Console (physician computer console) 24 associated with the scanner 22. After completion of the CT scan, the rectal catheter is removed, the gas is expelled, and the patient is 30 discharged.

The set of CT images 12 consisting of up to 500 images is then extracted, at step 50 of Fig. 1, from a database on the computer console 24 in

compressed format. Once the data has been extracted, the data is transferred from the console 24 at step 52 of Fig. 1, over a fiberoptic network 25, to a graphics computer work station 26, such as a Crimson VGXT 5 computer work station (150 MHz processor, 256 Mbytes RAM) from Silicon Graphics, Inc. (SGI, Mountain View, CA). The image files 12 are preferably transferred in the compressed format and then decompressed on the SGI graphics computer 26. Alternatively, the image files 10 can be decompressed on the GE computer console 24 and then transferred to the SGI graphics computer 26. The fiberoptic network 25 may comprise an ethernet network, asynchronous transfer mode (ATM) network, or a Fiber Distributed Data Interface (FDDI) network.

15 The extraction and transfer processes, 50 and 52, are performed by three program modules. To perform the extraction process 50, the first module residing on the computer console 24 extracts the images one at a time from the image database on the 20 computer console and places each extracted image file in a subdirectory on the computer console 24. In addition to the CT image files, a text file containing information about the patient and the type of case (e.g. colon) is placed in the subdirectory on the 25 computer console 24 so that the extracted image files are properly correlated with the appropriate patient and type of case. The second module, which resides on the graphics computer 26 is initiated every 5 minutes. The purpose of the second module is to transfer the 30 text file and corresponding image files from the computer console 24 to the graphics computer 26 and to delete such files from the computer console. The text file and image files are stored in a temporary directory on the graphics computer 26. The third

module is also initiated every 5 minutes and is interleaved with the second module. The third module determines if all of the files associated with a specific patient have been transferred to the graphics 5 computer. If all of the files of the specific patient have been transferred, the third module then organizes the transferred files in a patient subdirectory on the graphics computer 26 according to the case type. The entire process generally takes about 1 hour and is a 10 rate limiting step. The image transfer time can be reduced, however, by using the DICOM 3 image standard for data transmission.

Once the data transfer to the graphics computer 26 is complete, the compressed image data is 15 then decompressed, at step 55 of Fig. 1. The decompression of the image data is effected in accordance with a decompression scheme that is dependent on the specific compression formula used to originally compress the data. Different compression-decompression formulas may be used. After 20 decompression is complete, a volume of data 13 is then formed at step 60 of Fig. 1 by stacking the series of CT images 12 in computer memory. The formation of the volume of data 13 can be performed by using existing 25 volume formation programs, such as VoxelView™ (VitalImages, Fairfield, IA), or by using a customized program. Since each CT image 12 is approximately 0.5 megabytes in size, 500 images equates to about 30 250 megabytes. Therefore, a graphics computer 26 with sufficient memory, such as 256 Mbyte RAM, and adequate disc storage, such as greater than 1 gigabyte, is required.

Since rendering speed is inversely proportional to the size of the dataset, it is often necessary to reduce the size of the dataset of the three-dimensional volume 13 in order to perform three-dimensional rendering in real time. The process of dataset reduction is shown at step 65 of Fig. 1 and is illustrated in greater detail in Fig. 4. In the present application, the dataset is reduced from its original size, such as 250 megabytes, to a reduced size, such as 5-10 megabytes to expedite three-dimensional rendering. The dataset reduction may be partially accomplished by reducing the pixel resolution, for example, from 16 bits/pixel to 8 bits/pixel, as shown at step 67. The reduction in pixel resolution reduces the contrast in the final three-dimensional image by reducing the number of shades of gray from 2^{16} or 65,536 shades to 2^8 or 256 shades. In the field of radiology, the gray-scale shading of CT images correlates to x-ray attenuation which is measured in Hounsfield units (HU), and which ranges in value from -1024 to +3072. Water is assigned a value of 0 HU, soft tissue falls between 20 and 200 HU, contrast enhanced blood is > 125 HU, bones are > 250 HU, and air is less than -300 HU. In specific applications, the entire range of Hounsfield units may not be needed. Accordingly, a selected region of the scale may be used. For example, the upper and lower values of the region may be clipped prior to scaling. Since the regions above 300 HU and below -700 HU do not contain useful information for specific applications in rendering colons and airways, only the region values between 300 and -700 HU are scaled to the 256 shades of gray. The scaling is linear. However, non-linear scaling could be used to emphasize a particular region.

Further reduction of the dataset size can be effected by selecting a subvolume of the dataset to be displayed, as represented at step 68 of Fig. 4. Generally, the colon is subdivided into the rectum, 5 the sigmoid colon, the descending colon, the splenic flexure, the transverse colon, the hepatic flexure, the ascending colon, and the cecum. A separate subvolume may be assigned to selected subdivisions or sections of the colon. As shown in Fig. 7, a selected 10 subvolume 114 containing the entire colon and portions of the small bowel is specified by determining a set of minimum and maximum coordinates (X_{\min} , X_{\max} , Y_{\min} , Y_{\max} , Z_{\min} , and Z_{\max}) such that the selected subvolume 114 is defined by the selected coordinates. For example, 15 vertex 125 indicates X_{\min} , Y_{\min} , and Z_{\min} and vertex 126 indicates X_{\max} , Y_{\max} , and Z_{\max} . Using subvolumes reduces the size of the dataset and enables separate three-dimensional renderings of each selected subvolume.

If further dataset reduction is desired, the 20 dataset size can be decreased at step 69 of Fig. 4 by reducing the spatial resolution of the three-dimensional volume, for example, in the case of 500 images, from $512 \times 512 \times 500$ voxels to $256 \times 256 \times 250$ voxels. Since, reducing the spatial resolution can 25 blur the final three-dimensional image, decreasing the spatial resolution is generally not a preferred process for dataset reduction.

In general, the data reduction process 65 converts the initial volume of original CT images into 30 a transformed volume made of reduced CT images. The transformed volume is thereafter used to permit isolation of the targeted organ or other area of interest. The reduction of the dataset size may not

be necessary, however, if the graphics computer 26 has sufficient memory and processing capability relative to the size of the initial volume of original CT images to effect efficient three-dimensional
5 renderings.

In order to produce a three-dimensional rendering of only the colon, the colon must be isolated from the volume of data by image segmentation, as generally represented at step 70 in
10 Fig. 1 and as represented in greater detail in Fig. 5. Image segmentation can be performed before or after dataset reduction. A volume file pertaining to a patient is selected at step 71 of Fig. 1 and read at step 72 into the active RAM memory of the computer 26.
15 An optional Sample Crop procedure 73 for subcropping and/or subsampling the volume of data can be invoked to further reduce the volume of the dataset if desired. The Sample Crop procedure 73 enables the user to crop the volume of data along the X-axis, the
20 Y-axis and the Z-axis and further permits the user to subsample data, if desired, along each axis in order to further reduce the volume dataset. After the Sample Crop procedure 73, an Orthoslice procedure, as represented at step 74 in Fig. 5, is utilized to
25 select a slice through the volume. More specifically, an orthogonal slice through the volume is taken along the axial plane (a cross-sectional (X-Y) plane through the body perpendicular to the Z-axis and to the patient's spine), the coronal plane (a side-to-side
30 (X-Z) plane through the body normal to the Y-axis), or a sagittal plane (a front-to-back (Y-Z) plane through the body normal to the X-axis).

- The particular orthogonal plane and the specific location of the slice plane may be selected by the user. Preferably, the orthoslice is selected to pass through a complex portion of the anatomy. The 5 selected orthoslice is displayed at step 76 on the display monitor 28 of the graphics computer 26. After the orthoslice is selected and displayed, a thresholded version of the same image is also displayed on the monitor 28. A threshold range is 10 used at step 75 to define a range of x-ray attenuation values that represent the organ of interest. The region of interest may be the air column which designates the air and soft tissue interface of the colon wall.
- 15 The specific value of each pixel in the orthoslice corresponds to a physical property such as the x-ray attenuation at the location of each such pixel. To effect thresholding of the orthoslice, each individual pixel or grid position in the orthoslice is 20 compared, at step 75, to the selected threshold range to determine if each such pixel value lies in the designated threshold range. If an input pixel from the orthoslice falls within the thresholded range, such input pixel is set to a selected maximum value, 25 e.g. a value of 255 corresponding to a white color, in the thresholded image. Otherwise, the input pixel is set to a selected minimum value, e.g. a value of 0 corresponding to a black color, in the thresholded image to indicate that such input pixel from the 30 orthoslice falls outside the designated threshold range.

The threshold range can be deduced by the physician based on his/her experience as well as a

visual comparison of the orthoslice with the thresholded image. The thresholded image is displayed simultaneously with the orthoslice on display monitor 28, as indicated at step 76 of Fig. 5, to enable the 5 threshold range to be manually adjusted in real time to produce a good match between the thresholded image and the anatomical detail of the orthoslice. As shown in Fig. 8, the orthoslice is one of the reduced CT images 112 through the volume and it is displayed 10 alongside a corresponding thresholded image 115. The thresholded image 115 is a single reduced CT image that has been subjected to the acceptance criterion of the thresholding process. The threshold range is varied until the thresholded image 115 closely matches 15 the organ of interest in the orthoslice 112.

The threshold range thus obtained by thresholding the orthoslice is then applied globally to the volume of data at step 79 of Fig. 5 to create a thresholded volume. An exterior surface of equal 20 voxel value, or an isosurface 15, may be defined on the thresholded volume.

The isosurface 15 of the thresholded volume is then used as the basis for generating a wireframe model 16 of the colon as set forth in Fig. 5. As 25 illustrated in Fig. 9, a wireframe model 116 of the rectum portion of the colon is depicted in which the spatial resolution has been reduced from 512^3 to 256^3 . The vertices of the wireframe model 116 define a series of polygonal surfaces 136 that approximate the 30 surface of the organ of interest. Associated with each of the polygonal surfaces 136 is a vector which is perpendicular or normal to the surface 136. Various algorithms can be used for creating the

wireframe model 116 including, but not limited to, marching cubes, dividing cubes, and marching tetrahedrons. According to the marching cubes algorithm, the wireframe model 116 of the colon is
5 assembled by fitting a polygon or polygons through each voxel that is deemed to sit astride the isosurface 15 (i.e., through each voxel on the isosurface 15). The way in which the polygon or polygons are situated within each voxel depends upon
10 the distribution of the vertices of the voxel that lie inside and outside the surface. It is generally assumed that there are 15 possible distributions. The final position and orientation of each polygon within each voxel is determined by the strength of the
15 measured property at the vertices. The polygon or polygons are therefore an accurate representation of the surface as it passes through the voxel.

Since subjecting the entire data volume to simple thresholding may sometimes over/under estimate
20 the diameter of the colon and accentuate image noise, region growing and edge detection methods may be employed for segmenting the colon. A generalized region growing procedure 81 is set forth in Fig. 6. Region growing 81 can be used instead of the
25 thresholding procedure to effect segmentation of the organ or selected region of interest.

In region growing, a seed voxel is selected at step 82 which lies within the organ or region of interest. At step 83, the seed voxel is set to a
30 first value (i.e., 255 for white). The value of a neighboring voxel is then read at step 84. The value of the neighboring voxel is compared to a threshold range to determine if such neighboring voxel falls

within the acceptance threshold range at step 85. If the neighboring voxel falls within the acceptance range, the neighboring voxel is set to the same first value as the seed at step 86. The process then

5 returns to the seed voxel (i.e., neighbor-1) at step 87. A check is made, at step 88, to determine if all the voxels neighboring the seed voxel have been tested. If all the neighboring voxels have not been tested, another voxel neighboring the seed voxel is

10 read at step 84 and processing continues as described above. If all of the neighboring voxels have been tested at step 88, a new seed type voxel is picked at step 89. The new seed voxel is a voxel which has been determined to lie within the region of interest but

15 whose neighboring voxels have not yet been tested at step 85. Processing then continues at step 84, as described above.

Returning to step 85, if the neighboring voxel does not fall within the acceptance range, then

20 the neighboring voxel is set to a second value (i.e., 0 for black), at step 61, thereby indicating that the neighboring voxel lies at the edge of the region of interest. The process then returns to the seed voxel (i.e., neighbor-1) at step 87'. A check is then made,

25 at step 88', to determine if all the voxels neighboring the seed voxel have been tested. If all the neighboring voxels have not been tested, another voxel neighboring the seed voxel is read at step 84 and processing continues as described above. If all

30 of the neighboring voxels have been tested, a new seed type voxel is picked at step 89'. A check is then made, at step 88'', to determine if all the voxels neighboring the new seed type voxel have been tested. If all the neighboring voxels have not been tested, a

voxel neighboring the new seed type voxel is read at step 84 and processing continues as described above. If all the neighboring voxels have been tested, processing stops at step 62, thereby indicating that 5 the region of interest is completely bounded by edge voxels. In this manner, the organ of interest can be detected without subjecting the entire volume of data to thresholding. This technique is therefore capable of reducing the occurrence of artifacts (e.g., air 10 filled organs other than the organ of interest) in the final three-dimensional rendering.

As an alternative to setting the voxel value to a first or second value to indicate whether or not the voxel lies at the edge of the region of interest, 15 an unused, high order bit can be marked to indicate that the voxel lies at the edge. For example, if the voxel value is stored in the first 12 bits of a 16 bit variable, the last 4 bits can be used to indicate whether the voxel lies at the edge without altering 20 the information contained in the first 12 bits. This allows all of the information originally contained in the voxel value to be used for generating a wireframe model.

With simple thresholding or region growing, 25 the size of the object of interest can be either overestimated or underestimated, depending upon the chosen threshold range. To avoid overestimating or underestimating the size of the object of interest and to preserve the integrity of the model, the threshold 30 range determining the size of the object of interest can be intentionally underestimated and then the segmented object of interest can be adjusted using morphological dilation. Simple thresholding, as at

step 75 in Fig. 5, or region growing, as at step 85 in Fig. 6, can be used to underestimate the size of the object of interest by selecting a narrower thresholding range than would normally be used to
5 segment the particular object of interest. The size of the segmented object of interest is then increased by adding a "layer" of voxels to the segmented object of interest using morphological dilation. This is accomplished by adding all the voxels in the data
10 volume which are adjacent to the segmented object of interest to the segmented object of interest.

A process for morphological dilation is shown in Fig. 27. The process starts at step 300. At step 301 a voxel is selected. At step 306 it is
15 determined whether the voxel is marked as lying at the edge of the region of interest. If the voxel is marked as an edge voxel, then the process continues at step 308. If the voxel is not marked as an edge voxel, then the process proceeds to step 310. At
20 step 308, all of the voxels adjacent to the selected voxel are marked as belonging to the region of interest. Alternatively, a user-defined "thickness" of voxels can be added to the segmented object of interest. In such a case, all of the voxels within a
25 specified number of voxels from the selected voxel are marked as belonging to the region of interest. At step 310 it is determined whether all of the voxels have been analyzed. If all of the voxels have not been analyzed, then the process returns to step 301.
30 If all of the voxels have been analyzed, then the process ends at step 312.

The geometry of the wireframe model 16 is stored at step 78 of Fig. 5. The wireframe model is

stored in the form of a set of vertices and interconnecting line segments that define the wireframe model 16. The wireframe model 16 is then rendered into a three-dimensional image 17, as represented at step 80 in Figs. 1 and 5. As illustrated in Fig. 10, a three-dimensional image 117 of the rectum section of the colon has been rendered with reduced spatial resolution from the wireframe model 116 depicted in Fig. 9. Images of three-dimensional objects (wireframe models) in world coordinates (X, Y, Z) are projected to two-dimensional screen coordinates using ray-tracing techniques. Imaginary rays sent from a user's viewpoint pass through a viewing plane (referenced to a monitor screen) and into the object (wireframe model). If a ray intersects an object, the corresponding viewing plane pixel is painted with a color; if no intersection is found, the pixel is painted as background. The criteria used to stop a ray determines what value is projected onto the viewing plane pixel. Surface rendering as used to render the image of the rectum shown in Fig. 10 projects the first visible voxel. Volume rendering projects a weighted average of all voxels along a ray.

Animation of three-dimensional objects is achieved by rapidly displaying multiple three-dimensional views of the volume. Surface rendering calculations are fast enough to allow interactive manipulation (i.e., virtual reality) of the volume. Additional lighting techniques enhance an object's features by altering the shade of color of each viewing plane pixel. For example, "shaded surface" images add an illusion of depth by coloring pixels closer to the camera viewpoint with lighter shades.

Pixels in a shaded surface image reflect the distance between the anatomical structure and the user's viewpoint (not the original voxel values).

Information on the relative "position" of the user and
5 a virtual light source, along with the information about the wireframe model 16, are used to appropriately shade the wireframe model 16 to produce a realistic impression of the anatomy. The rendering process 80 can be accomplished using a general purpose
10 volume visualization program, such as *IRIS Explorer™*.

Alternatively, volume rendering can be used to animate three-dimensional objects. Unlike surface rendering which projects an image of a wireframe model, volume rendering projects a weighted average of
15 all voxels along a ray. The contrast of the three-dimensional image produced using volume rendering can be enhanced by assigning to each voxel an opacity value. The opacity value can be adjusted to make targeted anatomy opaque and undesired anatomy
20 transparent. In one embodiment, the assigned opacity values are the same for all voxels. In a second embodiment, the assigned opacity values are set randomly to produce a visually meaningful image while, for example viewing the image. In a third embodiment,
25 the opacity values vary as a function of voxel value. For example, the relation between opacity value and voxel value can be determined by calculating the inverse of the histogram curve and assigning the values found along this curve as opacity values. The
30 histogram curve reflects the number of voxels of a given voxel value as a function of voxel value.

The rendering step 80 occurs rapidly and interactively, thus giving the user the ability to

"fly" through the volume of data. The direction of "flight" is controlled by the computer mouse 27 through directional pointing of the cursor, and the speed (both backwards and forwards) is controlled by 5 pressing buttons on the computer mouse 27. The speed of interactive three-dimensional rendering produces a "virtual reality" environment and allows the user to examine the image data in a manner that is analogous to real endoscopy.

10 The path (camera coordinates) of each simulated flight can be stored and/or recorded. The stored path can be used in a "playback" mode to retrace the flight path. Individual three-dimensional scenes (views, images) may also be recorded (stored) 15 on the computer like photographs. The geometric representation of the wireframe model 16 of the colon and the volume dataset used to create the wireframe model are stored, at step 78 of Fig. 5, on digital audio tape (DAT) or, preferably, on read/write optical 20 discs. Each simulated "flight" through the colon can be recorded on VHS videotape on a video recorder 30 for archival purposes at step 90 of Fig. 1. Each flight may be recorded for later review by, for example, gastroenterologists and surgeons.

25 The recorded path can be used to allow the user to re-trace the path through the object of interest. This could assist the user if the user loses orientation or location during a flight through the object of interest. The user would back-up 30 through the recorded camera coordinates in reverse order until the user returned to a location within the object of interest which the user could identify. The

user could then continue the flight through the object of interest from that camera position.

To achieve an adequate speed of rendering (flying speed) but still preserve the anatomical 5 detail of the original CT data volume 13, it is possible to navigate or "fly" through reduced three-dimensional imagery based on a wireframe model 16 built from the reduced dataset volume. When the motion stops, however, the three-dimensional scene may 10 be redisplayed with the highest resolution possible using the original CT image volume 13.

Alternatively, the user can navigate through the three-dimensional imagery generated using surface rendering, select a point as the center of a 15 subvolume, and have a three-dimensional image of the subvolume rendered using volume rendering.

In addition to allowing the user to "fly" through the colon, the method of the present invention can be used to take the user on a guided tour of the 20 colon in an "auto-pilot" mode of operation. In the "auto-pilot" mode, the user is moved at a preselected speed through the three-dimensional representation of the colon along the center line of the lumen of the colon. The center line of the colon can be determined 25 in one of several ways. One method of determining the central path through the lumen of the colon is illustrated in Fig. 23. A seed point 91 is selected which lies within the lumen of the segmented colon 117''. The plane 92, passing through point 91 that 30 has the minimum area 93 of colon dissection is determined and the center 95 of such area 93 is calculated. A new point is then selected which lies

1cm away from center point 95 in a perpendicular direction relative to the surface area 93 in plane 92 as shown by arrow 94. A new plane of minimum area that dissects the colon and passes through the new 5 point is determined and the corresponding center of that new area is calculated. This iterative process is continued until a central path connecting the center points is determined.

Alternatively, repetitive morphological 10 "erosions" can be performed on the segmented colon through an iterative process analogous to removing "layers" of voxels. As each layer is eroded, the iterative level at which voxels disappear in each such layer is recorded. The erosion process is continued 15 until all of the voxels disappear. The central path through the colon is then constructed by connecting the highest valued voxels (i.e., the last voxels to disappear by erosion).

By determining the central path through the 20 colon, a single oblique (reformatted) plane (gray scale image) that is perpendicular to the central path at a certain point can be displayed thereby allowing simultaneous viewing of the wall thickness of the colon and surrounding anatomy and/or pathology during 25 the automatic flight. The oblique plane is perpendicular to the central path but is usually oblique relative to the three orthogonal planes.

The method of the present invention can also 30 be used to display the colon in a "split" open view 118, as shown in Fig. 12. A three-dimensional external rendering of the rectum 117' of the colon, as depicted in Fig. 11, can be split along the center

line to expose the interior surface 119 of a selected half of the colon. This split display mode is particularly advantageous when simultaneous viewing of extended sectional lengths of the colon is desired or
5 when viewing of the anatomy must be done with a computer that is not capable of rendering with real-time speed (i.e., not allowing the user to "fly" through the colon at a sufficiently fast speed).

The "split" view can be generated in one of
10 several ways. The first method is to define a cutting plane that is disposed parallel to the plane of the screen of the monitor 28 such that all portions of objects passing through the imaginary plane are made invisible as the objects are pulled closer to the
15 viewer and intersect the cutting plane. Defining a cutting plane is a standard part of Explorer's renderer (viewer). The three-dimensional object (colon) is rotated in space and moved closer to the user (viewer). As the colon passes through the
20 cutting plane, the half or portion of the colon closer to the user becomes invisible but the distant half or portion, with its surface detail, is available for inspection.

Another method for producing a split view is
25 to predefine subvolumes in accordance with step 68 of Fig. 4 so that a selected sectional length of colon is contained in two separate subvolumes corresponding to the two separate halves of the sectional length of the colon. That is, two separate subvolumes can be
30 created so that one subvolume shows one open half of the colon and the second subvolume shows the other open half. Defining the bounding points to thereby define a bounding subvolume may be done visually by

looking at orthoslices for representing the subvolume. It is faster to manipulate the two-dimensional orthoslice images rather than the three-dimensional volume. Once the bounding coordinates (X_{\min} , Y_{\min} , Z_{\min} , 5 and X_{\max} , Y_{\max} , Z_{\max}) are defined, then the subvolume representing one-half of a colon section is processed (rendered).

Another desired method for splitting the colon is to use an imaginary cutting plane (line) that 10 passes through the colon perpendicular to the central path through the lumen of the colon. The cutting line is maintained at a constant level parallel to the X-Z plane. All voxels on one side of the cutting line are made invisible (i.e., set to zero value or black, 15 since voxels in the segmented colon have been previously set to value 255 or white) and the white half of the colon is rendered. Then, the process is reversed and the other half of the colon is rendered. Alternatively, the wireframe model 16 may be split in 20 half prior to rendering.

An additional feature of the present invention is that an external map view 137 of the selected organ can be displayed, as shown in Fig. 13, 25 to assist the user if the user loses orientation or location during a flight through the lumen of the organ. Fig. 14 shows a three-dimensional rendering 117'' from inside the colon. If the user requests the display of a map view while inside the rendering 117'', 30 of the rectum shown in Fig. 14, the external map view 137 of Fig. 13 will be displayed with an indicator 138 for indicating the position of the three-dimensional rendering 117'' of Fig. 14. The indicator 138 can be a "+", as shown in Fig. 13, or any other selected

symbol. Preferably, the indicator 138 may be in the form of an arrow which also indicates the line of sight within the three-dimensional imagery.

Yet another feature of the present invention is that distances, areas, circumferences, and volumes can be measured directly from the three-dimensional image. To measure distances, the user would pick two points in the three-dimensional image and the distance between the points would be determined. Analogously, to measure cross-sectional areas of an object, the user would pick three points in the three-dimensional image thereby defining a plane passing through the object. The area of the plane bounded by the object's borders could then be determined. To measure volumes, the user could select a seed point within the object and then use region growing or region growing followed by morphological dilation to segment the desired structure. The volume of the segmented structure could then be determined. This feature is especially useful for monitoring the growth of lesions or polyps.

The method of the present invention is particularly well suited for identifying polyps and growths that extend into the lumen of the colon. However, some precancerous growths are manifested as a subtle thickening of the colon wall. The present invention can also be used to identify the areas of thickening as well. This can be accomplished by calculating and displaying a two-dimensional oblique plane perpendicular to the central axis of the colon whose location relative to the central path corresponds to the three-dimensional view at hand. Alternatively, a segmentation process could be used to isolate the colon wall instead of the air column

within the colon to determine the wall thickness. Pursuant to a texture mapping procedure, thickened areas or other areas of pathology can be visually distinguished from the normal wall of the colon in the 5 three-dimensional imagery by displaying the polygonal surfaces on the wireframe model that represent the thickened or pathological areas with a distinguishable color.

The method of the present invention can also 10 be used to display a tracheobronchial airway in three dimensions, in accordance with the general methods described in connection with Figs. 1 and 2 and with the system described in connection with Fig. 3. More specifically, a patient is initially prepared at 15 step 40 by administering a nonionic intravenous bolus of iodinated contrast agent with a power injector to aid in distinguishing the blood vessels surrounding the tracheobronchial airway. After an appropriate time delay (approximately 70 seconds), the patient is 20 scanned at step 45 from the thoracic inlet to the lung base to produce a series of two-dimensional images 12. The images 12 represent at least one physical property associated with the tracheobronchial airway. This 25 property may be, for example, the x-ray attenuation value measured with helical CT scanning. Preferably, the spacing between successive images 12 is approximately 1 mm to produce isocubic voxels.

The scans may be performed with a GE HiSpeed Advantage Helical CT Scanner 22 during a single 30 breath-hold acquisition which is completed in about 30 seconds. The scanning parameters may consist of a 0.12 inch (3 mm) x-ray beam collimation, 0.24 inch/sec (6 mm/sec) table speed (2:1 pitch), and a 0.04 inch

(1 mm) image reconstruction interval. As a result of the beam collimation and the reconstruction interval selected, there is considerable (2 mm) overlap between successive images 12. Typically, up to about 5 200 images are obtained. The images are stored in a compressed format on a GE computer console 24 associated with the scanner 22.

The series of CT scans is then extracted at step 50 from the image database on the computer console 24 in compressed format. Each compressed image represents a 512 x 512 image of picture elements, or pixels, and each pixel is comprised of 16 bits of data (16 bits/pixel). Once the data has been extracted, the data is transferred at step 52 over a 10 fiberoptic network 25 to the graphics computer work station 26, such as the Silicon Graphics Crimson VGXT computer work station (150 MHz processor, 256 Mbytes RAM). The image files 12 are preferably transferred in the compressed format and then decompressed at 15 step 55 on the graphics computer 26. The extraction and transfer steps are performed by three program modules. The first module residing on the computer console 24 extracts the images one at a time from the image database and places each extracted image in a 20 subdirectory on the computer console 24. In addition to the image files, a text file containing information about the patient and the type of case (i.e., lung) is created. The second module, which resides on the 25 graphics computer 26, is initiated every 5 minutes and transfers the patient's text file and image files from the computer console 24 to the graphics computer 26 and deletes such files from the computer console 24. The third module, which resides on the graphics 30 computer, is also initiated every 5 minutes and is

interleaved with the second module. The third module determines if all of the files associated with a patient have been transferred. If all of the files have been transferred, the third module organizes the
5 transferred files in a patient subdirectory according to the case type. The entire process generally takes about 1 hour and is a rate limiting step. The image transfer time can be reduced by utilizing the DICOM 3 image standard. Once the data transfer is complete,
10 the remaining steps are performed on the graphics computer 26.

A volume of data 13 is then formed at step 60 by stacking the series of CT images 12 in the computer memory. Since each CT image 12 is
15 approximately 0.5 megabytes in size, 200 images equates to about 100 megabytes. Therefore, a machine with sufficient memory and adequate storage is needed.

Since rendering speed is inversely proportional to the size of the volume of data to be
20 rendered, it is often necessary to reduce the size of the dataset in order to effectively perform three-dimensional rendering in real time. Dataset reduction is generally shown at step 65 of Fig. 1 and, more specifically, in Fig. 4. In application, the dataset
25 is reduced from 100 megabytes to about 5-10 megabytes. Dataset reduction is partially accomplished by reducing the pixel resolution from 16 to 8 bits/pixel, as represented at step 67. The reduction in pixel resolution reduces the contrast in the final displayed
30 images by reducing the number of shades of gray to 256. In the field of radiology, the gray scale shading of CT images corresponds to x-ray attenuation values measured in Hounsfield units (HU), which range

in value from -1024 HU to +3072 HU. Water is assigned a value of 0 HU, soft tissue falls between 20 and 200 HU, contrast enhanced blood is > 125 HU, bones are > 250 HU, and air is less than -300 HU. Since the
5 regions above 500 HU and below -700 HU do not contain information useful for rendering the bronchial airways, or the surrounding blood vessels and lymph nodes, the region between 500 and -700 HU is scaled to the 256 shades of gray. The scaling is linear.
10 However, non-linear scaling could be used to emphasize a particular region.

Further reduction of the dataset size can be accomplished by selecting a subvolume of the dataset to be displayed, as represented at step 68 of Fig. 4.
15 As illustrated in Fig. 15, a selected subvolume 214 is depicted containing the entire tracheobronchial airways. The bronchial airways are isolated from the entire thorax. The subvolume 214 is defined, as shown in Fig. 15, by determining a set of minimum and
20 maximum coordinates (X_{\min} , X_{\max} , Y_{\min} , Y_{\max} , Z_{\min} , Z_{\max}) so that the airways are contained within the subvolume 214 defined by the selected coordinates. For example, vertex 225 indicates coordinate X_{\min} , Y_{\min} , and Z_{\min} and vertex 226 indicates coordinate X_{\max} , Y_{\max} , and Z_{\max} .
25 The dataset size can be reduced further at step 69 of Fig. 4 by decreasing the spatial resolution, for example in the case of 200 images, from 512 x 512 x 200 voxels to 256 x 256 x 100 voxels. Since reducing the spatial resolution can blur the
30 final displayed images, decreasing the spatial resolution is generally not preferred.

The data reduction step 65 functions to convert the original volume of CT images into a volume of reduced CT images. The volume of reduced CT images is then used to construct the three-dimensional
5 imagery.

As represented at step 70 of Fig. 1, the bronchial airways are isolated within the volume of data by image segmentation. Image segmentation can be performed before or after dataset reduction. To
10 effect image segmentation, the volume file pertaining to the patient and case of interest are selected at step 71 of Fig. 5 and read at step 72 into the active RAM memory of the computer 26. An optional subcropping and/or subsampling step 73 can be
15 performed, if desired, to further reduce the size of the dataset. A threshold range is used to define a selected range of x-ray attenuation values contained within the organ of interest. Typically, the region of interest is the air column which designates the air
20 and soft tissue interface of the bronchial wall.

At step 74, an orthoslice is selected through a complex portion of the anatomy. The orthoslice is a cross-sectional two-dimensional slice (image) through the dataset parallel to one of the
25 primary planes (X-Y, X-Z, or Y-Z). The orthoslice is displayed on the monitor at step 76 as one of the reduced CT images through the volume. Alongside the reduced CT image, a thresholded image is also displayed at step 76. The displayed thresholded image
30 represents the orthoslice of the reduced CT image that has been subjected to an acceptance criterion of the thresholding process as previously described. As shown in Fig. 16, an orthoslice image 212 of the

airways is simultaneously displayed with a corresponding thresholded image 215. The thresholded image 215 in Fig. 16 is shown with the region of interest, the air column within the airways, in black.

5 The threshold range is varied until the displayed thresholded image 215 best matches the anatomical detail of the organ of interest in the displayed gray scale orthoslice image 212. The threshold range thus obtained is applied throughout the selected volume of

10 data to create a thresholded volume representing the airways. As an alternative to thresholding, a region growing procedure, as previously described and as represented in Fig. 6, may be employed to isolate the organ or region of interest. The region growing

15 procedure is able to reduce the occurrence of artifacts (i.e., air filled structures other than the organ of interest) in the three-dimensional imagery.

An isosurface 15 of the thresholded volume is then used as the basis for forming a wireframe model 16 of the bronchial airways. As shown in Fig. 17, a wireframe model 216 of the tracheobronchial airways is depicted. The vertices of the wireframe model 216 define a series of polygonal surfaces 236 that approximates the surface of the organ of

20 interest. Various algorithms can be used for creating the wireframe model 216 including, but not limited to, marching cubes, dividing cubes, and marching tetrahedrons.

25

The wireframe model 216 is rendered at step 30 80 of Fig. 1 into an interactive, three-dimensional display 217, as illustrated in Fig. 18. The rendering procedure can be accomplished using a general purpose volume visualization program, such as IRIS Explorer™.

The rendering procedure gives the user the ability to "fly" through the volume of data. The direction of "flight" is controlled by the orientation of the computer mouse. The speed of the "flight" (both 5 backwards and forwards) is controlled by pressing computer mouse buttons. Information on the relative "position" of the user and a virtual light source, along with the information from the wireframe model 216, are used to appropriately shade the 10 wireframe model 216 to give a realistic impression of the anatomy. Interactive three-dimensional rendering creates a perception of "virtual reality", and allows the user to examine the CT data in a way which is analogous to real bronchoscopy.

15 Each "flight" through the bronchial airways can be recorded on VHS videotape at video recorder 30, for archival purposes, as represented at step 90 of Fig. 1, and for later review by, for example, bronchoscopists and surgeons. In addition, each 20 flight through the airways can be recorded on the computer 26 by storing the path of movement as a set of coordinates reflecting the flight path through the three-dimensional imagery. For example, the appropriate coordinates of the path of movement may be 25 stored in computer memory as the path of movement is generated. The coordinates of the path of movement may be stored in a setting file on the computer 26 so that the path of movement may be reproduced (replayed) on the computer 26 at a later time. Individual three- 30 dimensional scenes (views, images) may also be recorded (stored) on the computer like photographs. The wireframe computer model of the bronchial airways can also be stored as represented at step 78 in Fig. 5

on digital audio tape (DAT) or, preferably, on read/write optical discs.

As an additional feature, selected "go to" points (three-dimensional views) may be generated and stored during a flight through the lumen of the organ. A "go to" procedure, generally designated 130, is represented in the flow chart of Fig. 25. During a flight through the organ, selected points of interest, such as three-dimensional scenes or views, may be recorded and assigned, at step 131, to buttons appearing on a general diagrammatic map of the particular organ being examined. The "go to" points on the map are stored, at step 132, in an appropriate setting file on the computer 26. In order to use the "go to" points, the user requests the display of the map of the organ at step 133. The "go to" points (buttons) appear on the map of the organ so that the user can move the mouse cursor to a selected button, at step 134, and then click a mouse button so that the displayed three-dimensional view is transformed to the chosen view at step 135. In application with the colon imagery, separate "go to" points may be assigned to respective sections corresponding to the rectum, sigmoid colon, descending colon, splenic flexure, transverse colon, hepatic flexure, ascending colon and cecum. For the tracheobronchial airways, separate "go to" points may be assigned to respective sections corresponding to the trachea, carina, right upper lobe bronchus, right middle lobe bronchus, right lower lobe bronchus, left upper lobe bronchus, and left lower lobe bronchus.

The system 20 also provides the user with the ability to display the three orthogonal slices

(along the axial, coronal, and sagittal axes) which pass through any selected "pick point" in the three-dimensional imagery. This is accomplished by pointing the computer mouse cursor at the desired location in

5 the three-dimensional imagery and "clicking" on that point with a computer mouse button. The point of intersection with the first visible surface in the three-dimensional imagery is captured. The three-dimensional coordinate (X,Y,Z position) of the point

10 of intersection is used to calculate the three orthogonal planes (axial, sagittal, coronal) that pass through that point. The axial plane is parallel to the X-Y axes, the sagittal plane is parallel to the Y-Z axes, and the coronal plane is parallel to the X-Z axes.

15 As shown in Fig. 26, the three orthogonal planes passing through a selected pick point in the tracheobronchial airways are displayed in three separate windows (140, 141, and 142) together with a main window 143 containing the three-dimensional image

20 217''' of the tracheobronchial airways. Cross-hairs are overlaid on each orthogonal plane image indicating the position of the pick point. By moving the mouse cursor over one of the orthogonal images, the cross-hairs in that image follow the position of the cursor.

25 As the position of the cross-hair changes, the other two orthogonal images and their cross-hairs change to reflect the new position of the point in three-dimensional space. The three-dimensional image in the main window remains frozen during this time and does

30 not change. The usefulness of this function is that it allows a physician to view and pan through the reduced volume CT image data that surrounds the pick point. In using this process, wall thickness at a selected location may be determined. In addition,

35 surrounding anatomical structure or pathology may also

be viewed. In addition to "clicking" on a single pick point in the three-dimensional imagery, the user may activate a selected combination of mouse buttons while moving the mouse through the three-dimensional

5 imagery. The points of intersection are immediately calculated and the corresponding orthogonal planes are displayed. This mouse dragging procedure is analogous to "dragging" your finger across the surface of the anatomy and displaying the orthoslices interactively.

10 Alternatively, a pick point in the center of the three-dimensional image can be automatically determined and the corresponding orthogonal planes displayed, with the orthogonal planes being continually updated as the user moves through the

15 three-dimensional image.

The method of the present invention also provides the ability to render portions of a region of interest transparent or semi-transparent. Typically, the tracheobronchial airway can be rendered semi-transparent or completely transparent to allow the user to "see" beyond the wall of the airway and locate various anatomical structures, such as lymph nodes and blood vessels. This aspect of the present invention is particularly useful as a guide for Transbronchial

20 Needle Aspiration (TBNA). For example, needle placement can be guided to a selected location through the tracheobronchial wall. Making the tracheobronchial wall transparent to reveal surrounding blood vessels and lymph nodes may serve to

25 30 prevent unintentional puncture of blood vessels and lymph nodes during needle insertion.

Referring to Fig. 24, a procedure 100 for making a selected organ transparent for the purpose of

revealing surrounding organs is depicted. After a volume of reduced CT images is generated at the selected area of interest, selected organs, such as the tracheobronchial airway, the surrounding blood vessels and the surrounding lymph nodes, are segmented from the volume of reduced CT images. At step 70', the air column representing the tracheobronchial airway is segmented. At step 70'', the blood vessels are segmented and at step 70''' the lymph nodes are segmented. The order in which selected organs are segmented may be varied. In addition, each organ may be segmented using a thresholding procedure or the region growing technique.

If thresholding is employed for organ segmentation, the air column representing the tracheobronchial airway may be assigned a range less than -300 HU. The soft tissue representing the lymph nodes may be thresholded in the range of 30 to 80 HU. The blood vessels may be thresholded according to the contrast agent contained within the blood so that the blood vessels are thresholded in the range greater than 125 HU.

After the appropriate wireframe models 16 are generated for the respective organs, the airways, 25 blood vessels and lymph nodes are rendered together in the same three-dimensional scene at step 80' of Fig. 24 for display on the screen of the monitor. To better distinguish between respective organs, each wireframe model may be produced in a separate color.

At step 101 of Fig. 24, one of the organs is selected for transparency. Then, at step 102, the degree of transparency is selected. The degree of

transparency may be selected by a sliding scale from 0 to 100%. In application, the walls of the tracheobronchial airway may be selected to be displayed transparently, therefore the view from 5 within the lumen of the tracheobronchial airway enables the location of the surrounding blood vessels and lymph nodes to be seen.

The method of the present invention can also be used to display the tracheobronchial tree in a 10 "split" view 218, as shown in Fig. 20. A three-dimensional rendering 217' of a selected section of the tracheobronchial tree, as shown in Fig. 19, can be split along the center line to expose the interior surface 219 of the tracheobronchial tree.

15 An additional feature of the present invention is that an external map view 237 can be displayed as shown in Fig. 21. Fig. 22 shows a three-dimensional rendering 217'' from inside the tracheobronchial tree entering the left mainstem 20 bronchus. Fig. 21 shows an external map view 237 with an indicator 238 for indicating the position within the tracheobronchial tree from which the rendering 217'' in Fig. 22 is taken. The indicator 238 can be a "+", as shown in Fig. 21, or any other symbol, such as 25 an arrow which also indicates the line of sight within the three-dimensional imagery.

The present invention is not limited to the use of images obtained from CT scanners. The present invention works equally well with tomographic x-ray 30 data, ultrasound, positron emission tomography, emission computed tomography, and magnetic resonance images. In addition, although the present invention

has been discussed in reference to its usefulness in examining the colon and the tracheobronchial tree, the present invention is also useful in rendering three-dimensional images of other passageways and anatomical structures, such as arteries, veins, solid viscera, stomachs, bladders, bone, and ventricles of the brain.

It will be recognized by those skilled in the art that changes or modifications may be made to the above-described embodiments without departing from the broad inventive concepts of the invention. It should therefore be understood that this invention is not limited to the particular embodiments described herein, but is intended to include all changes and modifications that are within the scope and spirit of the invention as set forth in the claims.

THE CLAIMS DEFINING THE INVENTION ARE AS FOLLOWS:

1. A method for interactively displaying three-dimensional structures comprising the steps of:
 - 5 a. forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body;
 - b. segmenting a selected region of interest from the volume of data based on selected values of the physical property representing the selected region of interest; and
 - c. rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest therein producing a virtual three-dimensional environment.
- 10 2. The method as recited in claim 1 comprising a reduction step of reducing the size of the volume of data before rendering the image of the segmented region of interest in the interactive three-dimensional display.
- 15 3. The method as recited in claim 2 wherein the reduction step comprises reducing pixel resolution.
- 20 4. The method as recited in claim 3 wherein the pixel resolution is reduced to 8 bits per pixel.
- 25 5. The method as recited in claim 2 wherein the reduction step comprises reducing spatial resolution.
6. The method as recited in claim 5 wherein the spatial resolution is reduced to 256 pixels by 256 pixels.
- 30 7. The method as recited in claim 2 wherein the reduction step comprises creating a sub-volume of data.



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8. The method as recited in claim 1 wherein the series of two-dimensional images comprises images taken at regularly spaced grid locations within the body.

9. The method as recited in claim 8 wherein the spacing between successive grid 5 locations is selected to produce isocubic voxels for the three-dimensional display.

10. The method as recited in claim 1 wherein the physical property includes x-ray attenuation.

10 11. The method as recited in claim 1 wherein the series of two-dimensional images comprises images taken at 1 mm regularly spaced grid locations within the body.

12. The method as recited in claim 1 wherein the series of two-dimensional images comprises computed tomography images.

15

13. The method as recited in claim 12 wherein the computed tomography images comprise helical computed tomography images.

20

14. The method as recited in claim 1 wherein the series of two-dimensional images comprises x-ray Images.

15. The method as recited in claim 1 wherein the body comprises a human body.

16. The method as recited in claim 1 wherein the selected region of interest comprises an 25 air column within a body organ.

17. The method as recited in claim 16 wherein the air column comprises a colon.

18. The method as recited in claim 16 wherein the air column comprises the bronchi.

30



19. The method as recited in claim 16 wherein the air column comprises a larynx.
20. The method as recited in claim 16 wherein the air column comprises a trachea.
- 5 21. The method as recited in claim 1 wherein the region of interest comprises an air-tissue interface at a body organ.
22. The method as recited in claim 1 wherein the step of segmenting the selected region of interest comprises a thresholding step for determining threshold values corresponding to 10 the selected values of the physical property to isolate the selected region of interest.
23. The method as recited in claim 22 including forming an isosurface wireframe model of the isolated selection region of interest.
- 15 24. The method as recited in claim 23 wherein the step of rendering an image includes the step of rendering a three-dimensional display of the wireframe model.
25. The method as recited in claim 24 wherein the step of rendering a three-dimensional display of the wireframe model comprises a volume rendering step.
- 20 26. The method as recited in claim 25 wherein the volume rendering step comprises an opacity adjusting step for adjusting opacity values.
27. The method as recited in claim 26 wherein the opacity adjustment step comprises the 25 step of adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.
28. The method as recited in claim 22 wherein the thresholding step comprises:
 - a. a threshold selection step for selecting a threshold range corresponding to the 30 selected values of the physical property representing the selected region of interest; and



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b. a threshold adjustment step for adjusting the threshold values to provide the threshold range for isolating the selected region of interest.

29. The method as recited in claim 28 wherein the threshold adjustment step comprises:

- 5 a. an orthoslice step of providing an orthoslice through the volume of data; and
 b. a display step for displaying the orthoslice and a corresponding thresholded image of the orthoslice, so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice.

10 30. The method recited in claim 29 wherein the thresholding step comprises:

- a. a threshold selection step for selecting a threshold range corresponding to the selected values of the physical property representing the selected region of interest; and
 b. a threshold adjustment step for adjusting the threshold values to provide the threshold range for isolating the selected region of interest.

15

31. The method as recited in claim 22 wherein the step of segmenting the selected region of interest comprises a morphological dilation step.

20

32. The method as recited in claim 31 including forming an isosurface wireframe model of the isolated selected region of interest.

33. The method as recited in claim 32 wherein the step of rendering an image includes the step of rendering a three-dimensional display of the wireframe model.

25 34. The method as recited in claim 31 wherein the threshold adjustment step comprises:

- a. an orthoslice step of providing an orthoslice through the volume of data; and
 b. a display step for displaying the orthoslice and a corresponding thresholded image of the orthoslice, so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice.

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35. The method as recited in claim 31 wherein the morphological dilation step comprises the steps of:

- i. under segmenting the selected region of interest from the volume of data; and
- ii. adding a layer of voxels to the undersegmented region of interest to form a

5 segmented region of interest.

36. The method as recited in claim 22 wherein the thresholding step comprises:

- i. a threshold selection step for selecting a threshold range corresponding to the selected values of the physical property representing the selected region of interest; and
- 10 ii. a threshold adjustment step for adjusting the threshold values to provide the threshold range for isolating the selected region of interest.

37. The method as recited in claim 36 wherein the threshold adjustment step comprises:

- a. an orthoslice step of providing an orthoslice through the volume of data; and
- 15 b. a display step for displaying the orthoslice and a corresponding thresholded image of the orthoslice so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice.

38. The method as recited in claim 22 wherein the step of segmenting the selected region
20 of interest comprises a morphological dilation step.

39. The method as recited in claim 38 wherein the morphological dilation step comprises the steps of:

- i. undersegmenting the selected region of interest from the volume of data; and
- 25 ii. adding a layer of voxels to the undersegmented region of interest to form a segmented region of interest.

40. The method as recited in claim 38 including forming an isosurface wireframe model of the isolated selected region of interest.



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41. The method as recited in claim 40 wherein the step of rendering an image includes the step of rendering a three-dimensional display of the wireframe model.

42. The method as recited in claim 1 wherein the region of interest comprises a tissue-bone interface.

43. The method as recited in claim 1 wherein the region of interest comprises an air-bone interface.

10 44. The method as recited in claim 1 wherein the rendering step includes the steps of splitting the three-dimensional display open in selected split open sections and displaying the split open sections so that inner surfaces of the split three-dimensional display are visible.

15 45. The method as recited in claim 44 wherein the splitting step comprises the step of splitting the three-dimensional display open along a line which passes along the center of the three-dimensional display.

20 46. The method as recited in claim 1 comprising the step of simulating movement along a center line through the segmented region of interest of the virtual three-dimensional environment.

47. The method as recited in claim 46 wherein the step of splitting the three-dimensional display open along a line which passes along the center of the three-dimensional display includes the steps of:

- 25 a. selecting a seed point which lies within the region of interest;
 b. determining a plane of minimum area through the region of interest that passes through the seed point;
 c. determining the center point of the region of interest that is dissected by the plane of minimum area; and
30 d. selecting a point which is spaced from the center point in a perpendicular



direction relative to the plane of minimum area.

48. The method as recited in claim 46 wherein the step of splitting the three-dimensional display open along a line which passes along the center of the three-dimensional display
5 includes the steps of:

- a. iteratively eroding the region of interest until all of the region of interest disappears, thereby determining the last portion of the region of interest to disappear; and
- b. connecting the last portion of the region of interest to disappear by erosion.

10 49. The method as recited in claim 1 wherein the rendering step includes the steps of splitting the three-dimensional display open in selected split open sections, therein producing an interactive, cross-sectional, three-dimensional rendering and displaying the interactive, cross-sectional, three-dimensional rendering so that inner surfaces of the split three-dimensional display are visible.

15

50. The method as recited in claim 49 wherein the splitting step includes the steps of:

- a. defining a cutting plane through the segmented region of interest; and
- b. rendering all portions of the three-dimensional display on one side of the cutting plane transparent.

20

51. A method for interactively displaying a colon in three dimensions comprising:

- a. an image acquisition step wherein a series of two-dimensional images representing least one physical property associated with the colon is acquired;
- b. a volume formation step wherein a three-dimensional volume of data is formed
25 by stacking the series of two-dimensional images in computer memory;
- c. a segmentation step wherein a region of interest related to the colon is segmented from the volume of data based on selected values of the physical property representing the region of interest; and
- d. a rendering step wherein the segmented region of interest is rendered in an
30 interactive three-dimensional display for interaction with internal surfaces of the segmented



- 59 -

region of interest, therein producing a virtual three-dimensional environment.

52. The method as recited in claim 51 comprising cleansing the colon before the image acquisition step.

5

53. The method as recited in claim 51 comprising inflating the colon with gas before the image acquisition step.

54. The method as recited in claim 51 wherein the series of two-dimensional images
10 comprises images taken at regularly spaced grid locations within the body.

55. The method as recited in claim 54 wherein the spacing between successive grid locations is selected to produce isocubic voxels for the three-dimensional display.

15 56. The method as recited in claim 54 wherein the series of two-dimensional images
comprises images taken at 1 mm regularly spaced grid locations within the body.

57. The method as recited in claim 54 wherein the spacing between successive grid locations is selected to produce an overlap between successive images.

20

58. The method as recited in claim 51 wherein the physical property includes x-ray attenuation.

59. The method as recited in claim 51 wherein the series of two-dimensional images
25 comprises computed tomography images.

60. The method as recited in claim 59 wherein the computed tomography images comprise helical computed tomography images.

30 61. The method as recited in claim 51 wherein the region of interest comprises an air-



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tissue interface.

62. The method as recited in claim 51 further comprising a data reduction step for reducing the size of the volume of data before rendering the segmented region of interest.

5

63. The method as recited in claim 62 wherein the reduction step comprises reducing pixel resolution.

64. The method as recited in claim 63 wherein the pixel resolution is reduced to 8 bits per 10 pixel.

65. The method as recited in claim 62 wherein the reduction step comprises reducing spatial resolution.

15 66. The method as recited in claim 65 wherein the spatial resolution is reduced to 256 pixels by 256 pixels.

67. The method as recited in claim 62 wherein the reduction step comprises creating a sub-volume of data.

20

68. The method as recited in claim 67 wherein the sub-volume is a sub-volume containing at least one of the rectum, the sigmoid colon, the descending colon, the splenic flexure, the transverse colon, the hepatic flexure, the ascending colon, and the cecum.

25 69. The method as recited in claim 62 wherein the size of the volume of data is reduced to less than about 10 megabytes.

70. The method as recited in claim 51 wherein the rendering step comprises simulating movement along a line which passes along the center of the lumen of the colon.

30



71. The method as recited in claim 51 wherein the rendering step comprises splitting the colon open in lengthwise sections and displaying the split open colon so that inner surfaces of the split open colon are visible.

5 72. The method as recited in claim 51 wherein the segmentation step comprises a step of determining colon wall thickness.

73. The method as recited in claim 72 wherein the step of determining the colon wall thickness comprises displaying a cross-sectional image through the colon.

10

74. The method as recited in claim 72 wherein the step of determining colon wall thickness comprises a step of identifying a thickened section of the colon by visually differentiating a thickened section on a displayed image from normal thickness of the colon wall.

15

75. The method as recited in claim 51 wherein the volume rendering step comprises an opacity adjusting step for adjusting opacity values.

20

76. The method as recited in claim 75 wherein the opacity adjustment step comprises the step of adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.

77. The method as recited in claim 51 comprising an opacification step for homogeneously opacifying feces.

25

78. A method for interactively displaying a tracheobronchial airway in three dimensions comprising:

a. an image acquisition step wherein a series of two-dimensional images representing at least one physical property associated with the tracheobronchial tree is

30 acquired;



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b. a volume formation step wherein a three-dimensional volume of data is formed by stacking the series of two-dimensional image in computer memory;

c. a segmentation step wherein a region of interest is segmented from the volume of data based on selected values of the physical property representing the region of interest;

5 and

d. a rendering step wherein the segmented region of interest is rendered in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.

10 79. The method as recited in claim 78 wherein the image acquisition step comprises a patient preparation step wherein a patient is administered a nonionic intravenous iodinated contrast bolus.

15 80. The method as recited in claim 78 wherein the series of two-dimensional images comprises images taken at regularly spaced grid locations within the body.

81. The method as recited in claim 80 wherein the spacing between successive grid locations is selected to produce isocubic voxels for three-dimensional display.

20 82. The method as recited in claim 80 wherein the series of two-dimensional images comprises images taken at 1 mm regularly spaced grid locations within the body.

83. The method as recited in claim 82 wherein the spacing between successive grid locations is selected to produce an overlap between successive images.

25

84. The method as recited in claim 80 wherein the physical property includes x-ray attenuation.

85. The method as recited in claim 80 wherein the series of two-dimensional images 30 comprises computed tomography images.



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86. The method as recited in claim 85 wherein the computed tomography images comprise helical computed tomography images.

87. The method as recited in claim 78 wherein the region of interest comprises an air
5 column.

88. The method as recited in claim 78 comprising a data reduction step for reducing the size of the volume of data before rendering the segmented region of interest.

10 89. The method as recited in claim 88 wherein the reduction step comprises reducing pixel resolution.

90. The method as recited in claim 89 wherein the pixel resolution is reduced to 8 bits per pixel.

15

91. The method as recited in claim 88 wherein the reduction step comprises reducing spatial resolution.

92. The method as recited in claim 91 wherein the spatial resolution is reduced to 256
20 pixels by 256 pixels.

93. The method as recited in claim 88 wherein the reduction step comprises creating a sub-volume of data.

25 94. The method as recited in claim 93 wherein the sub-volume comprises the mediastinum.

95. The method as recited in claim 88 wherein the size of the data is reduced to less than about 10 megabytes.

30



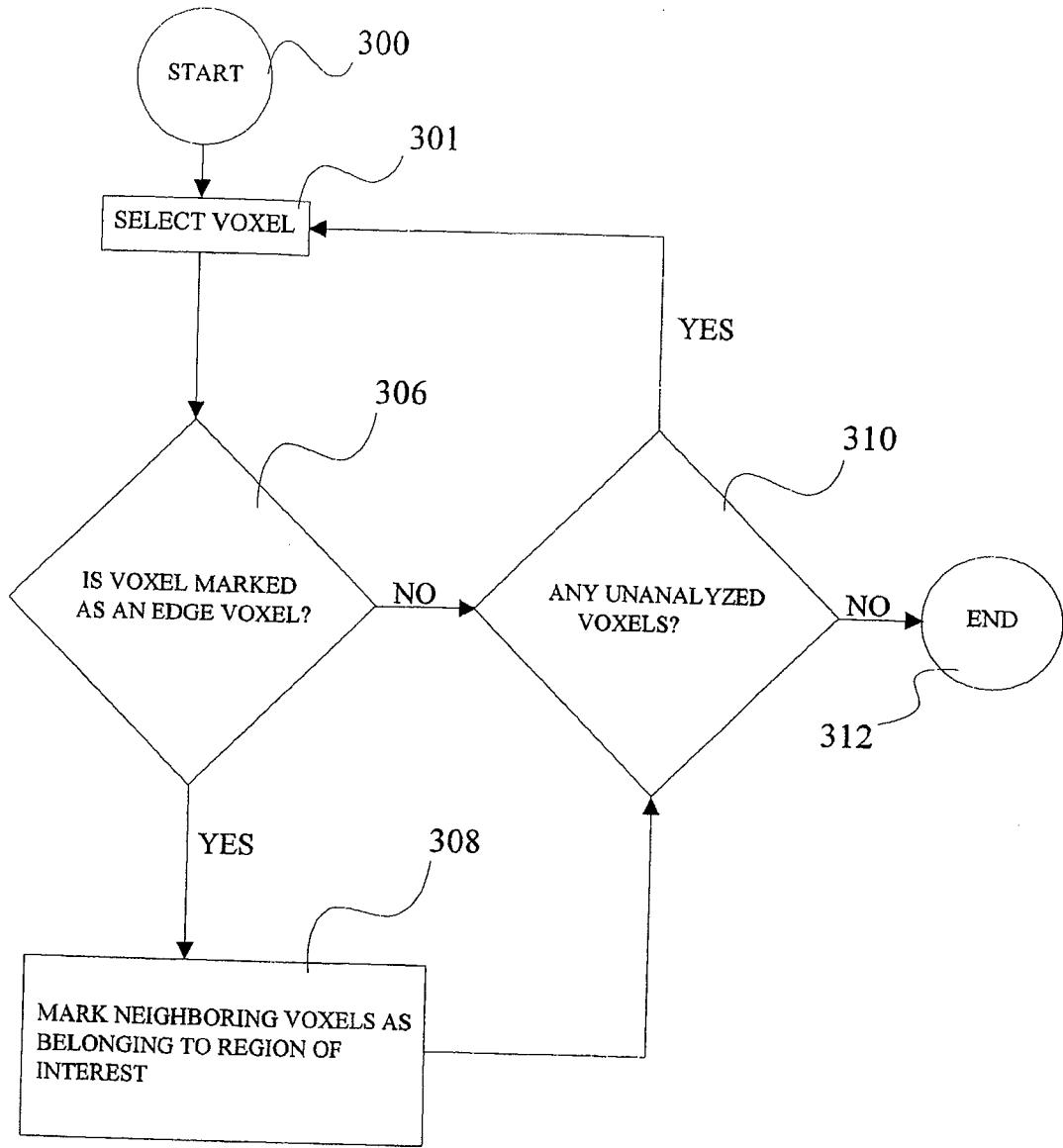


Fig. 27

8
9
10
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12

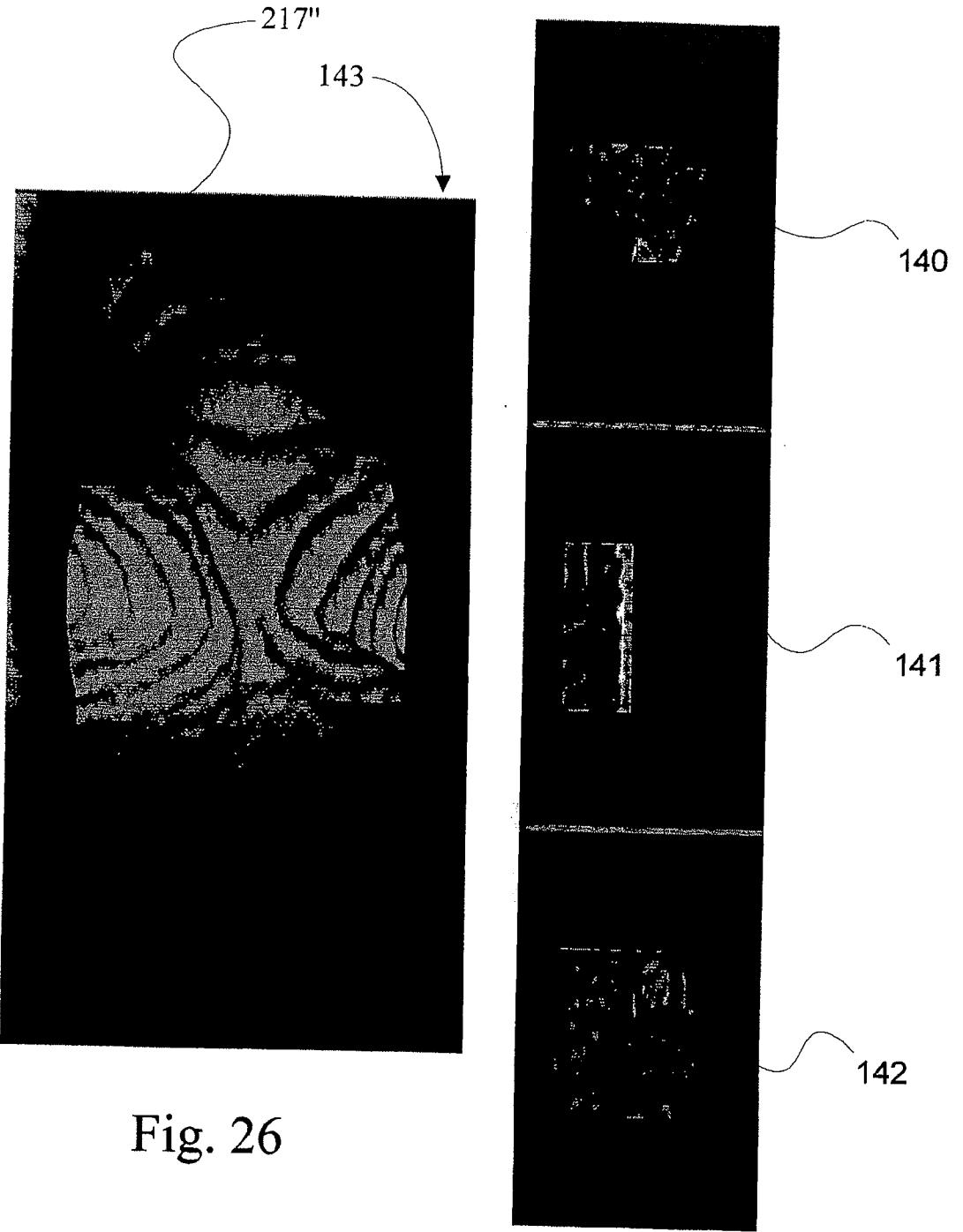


Fig. 26

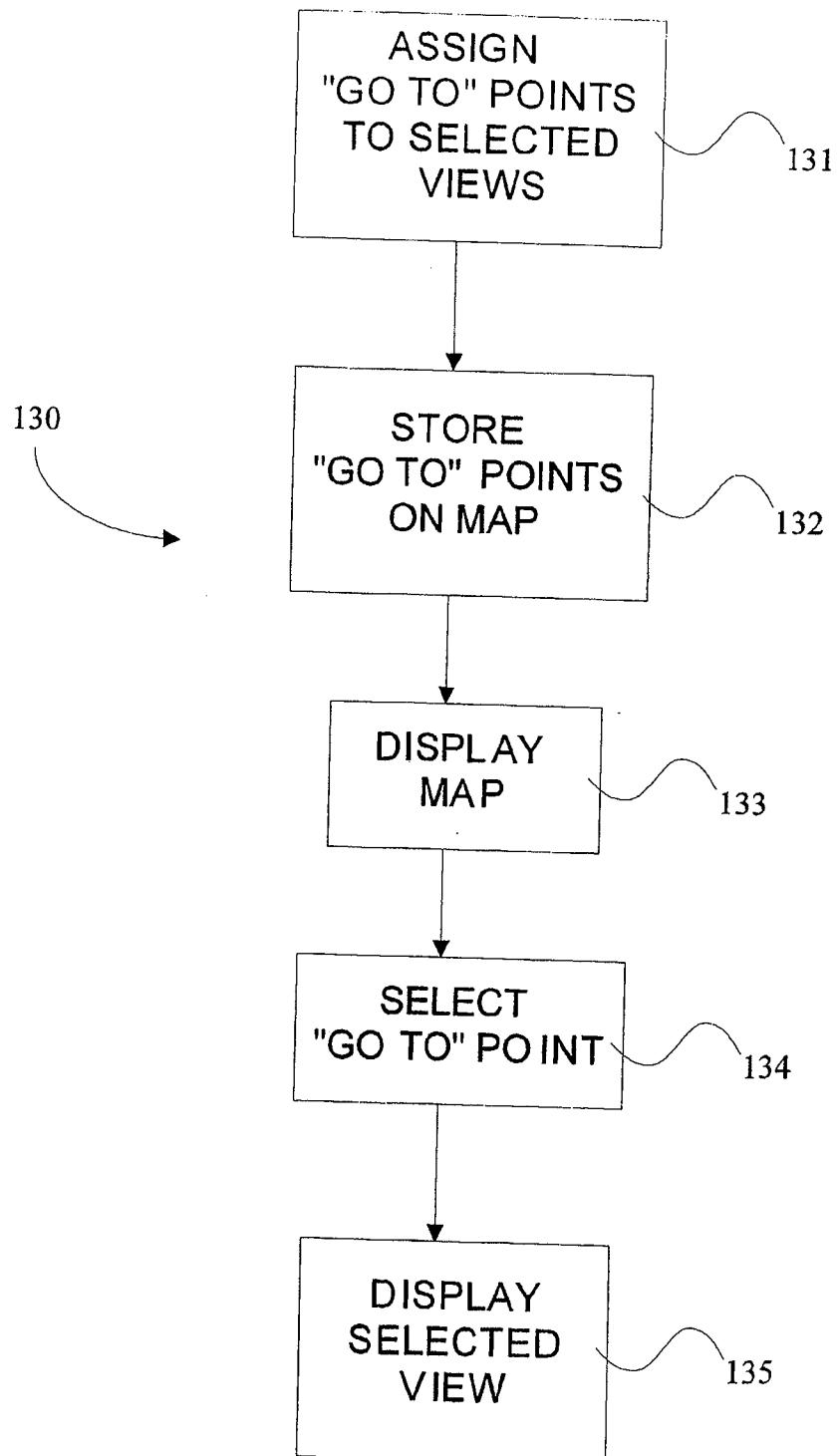


Fig. 25

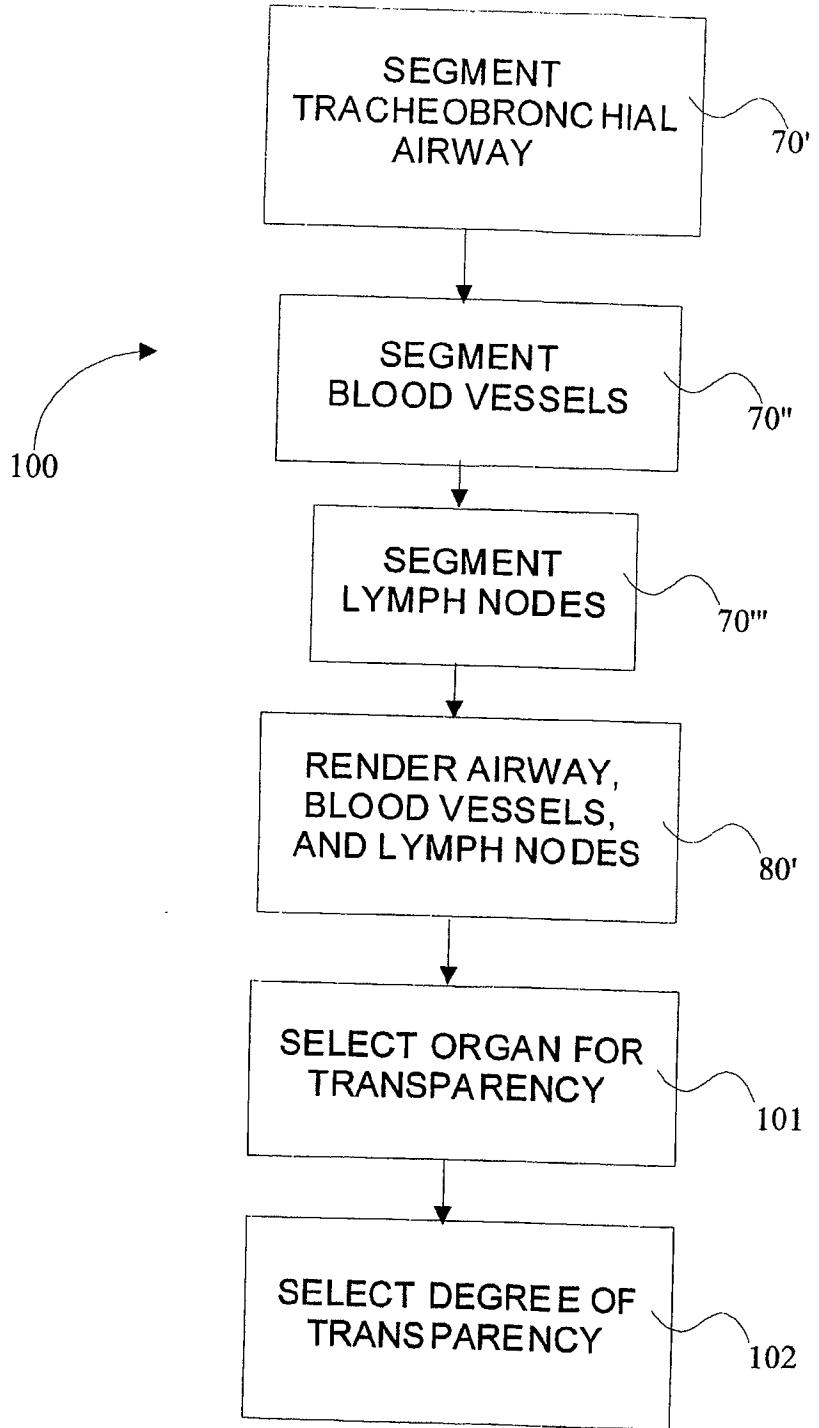


Fig. 24

BR
+
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34

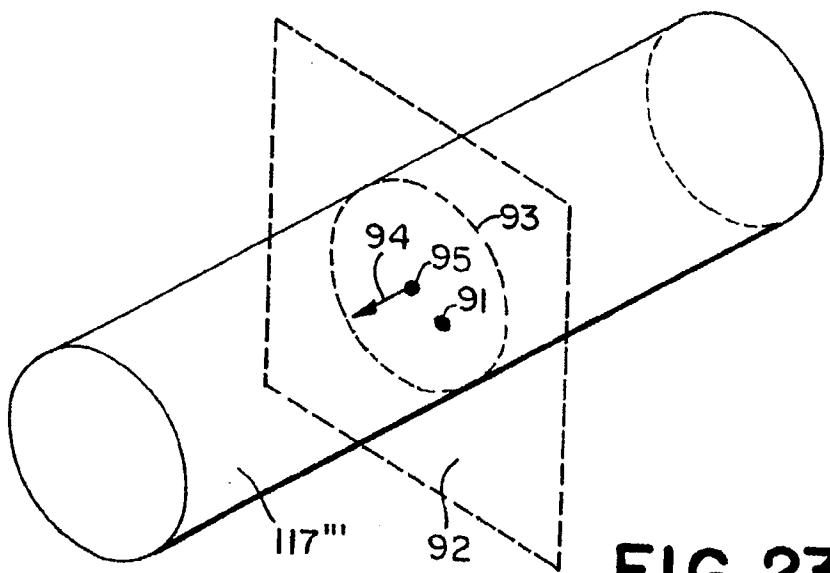


FIG. 23

88
3
88
89



Fig. 22

238
237
236
235
234

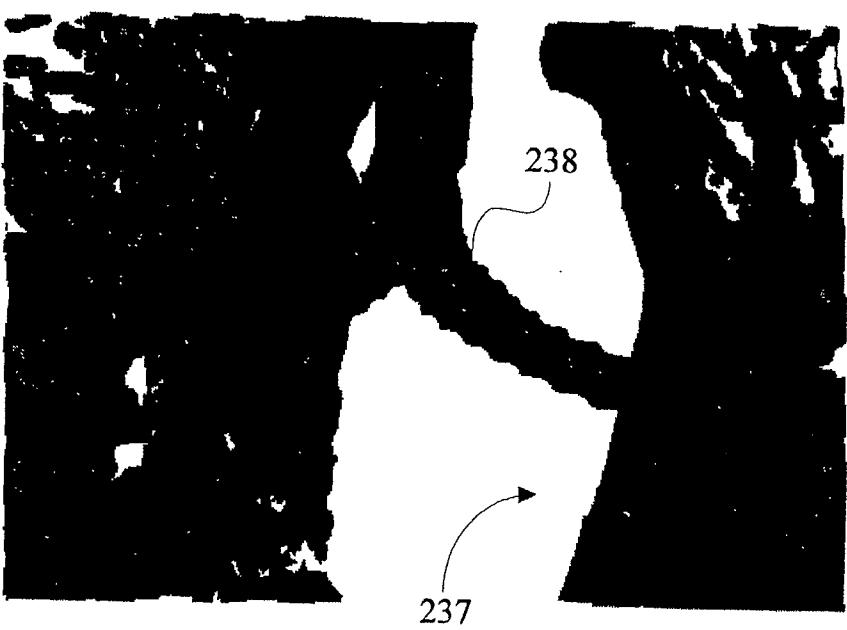


Fig. 21

218
219

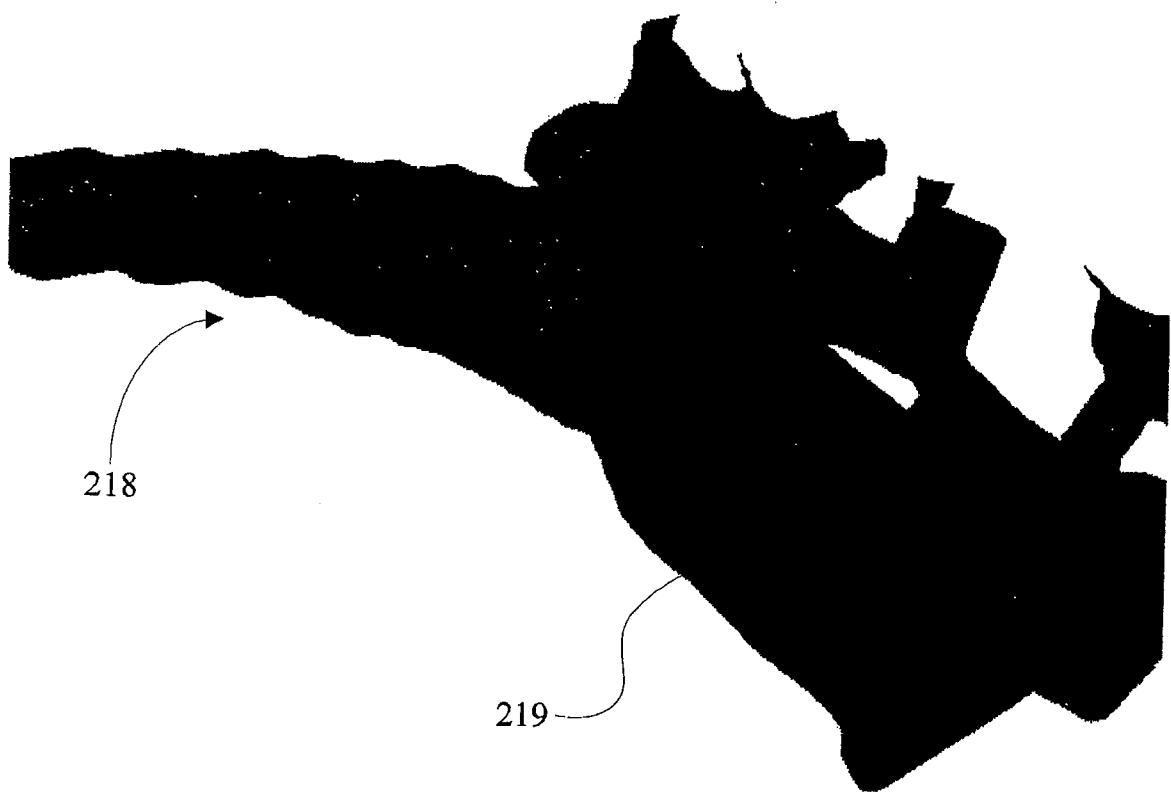


Fig. 20

89
88
87
86
85

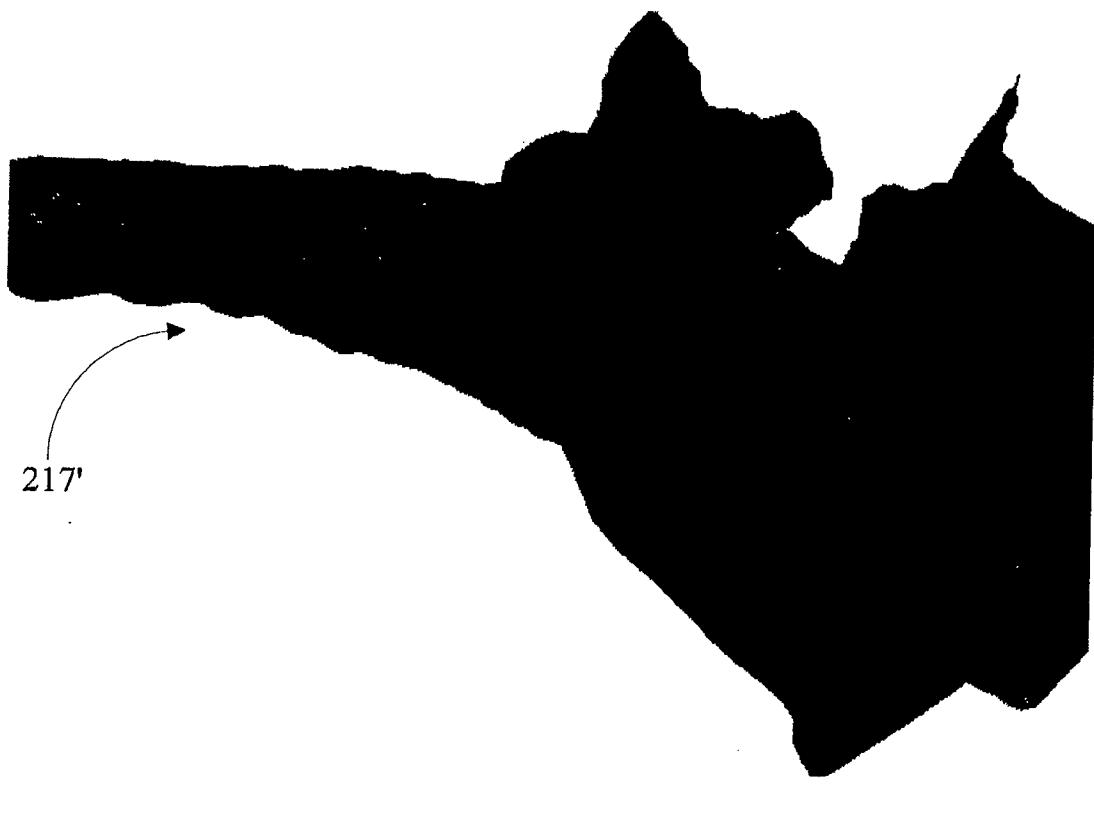


Fig. 19

217
218
219
220
221

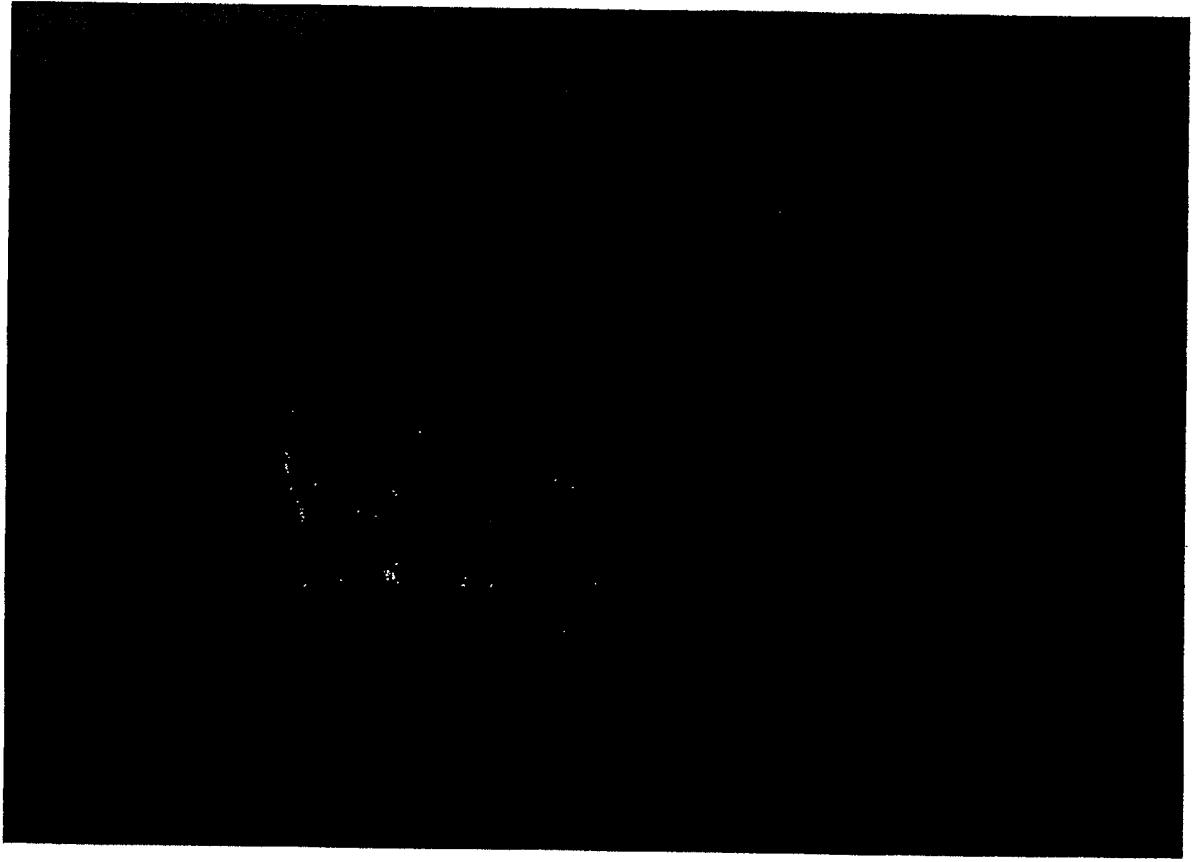


Fig. 18

236
216

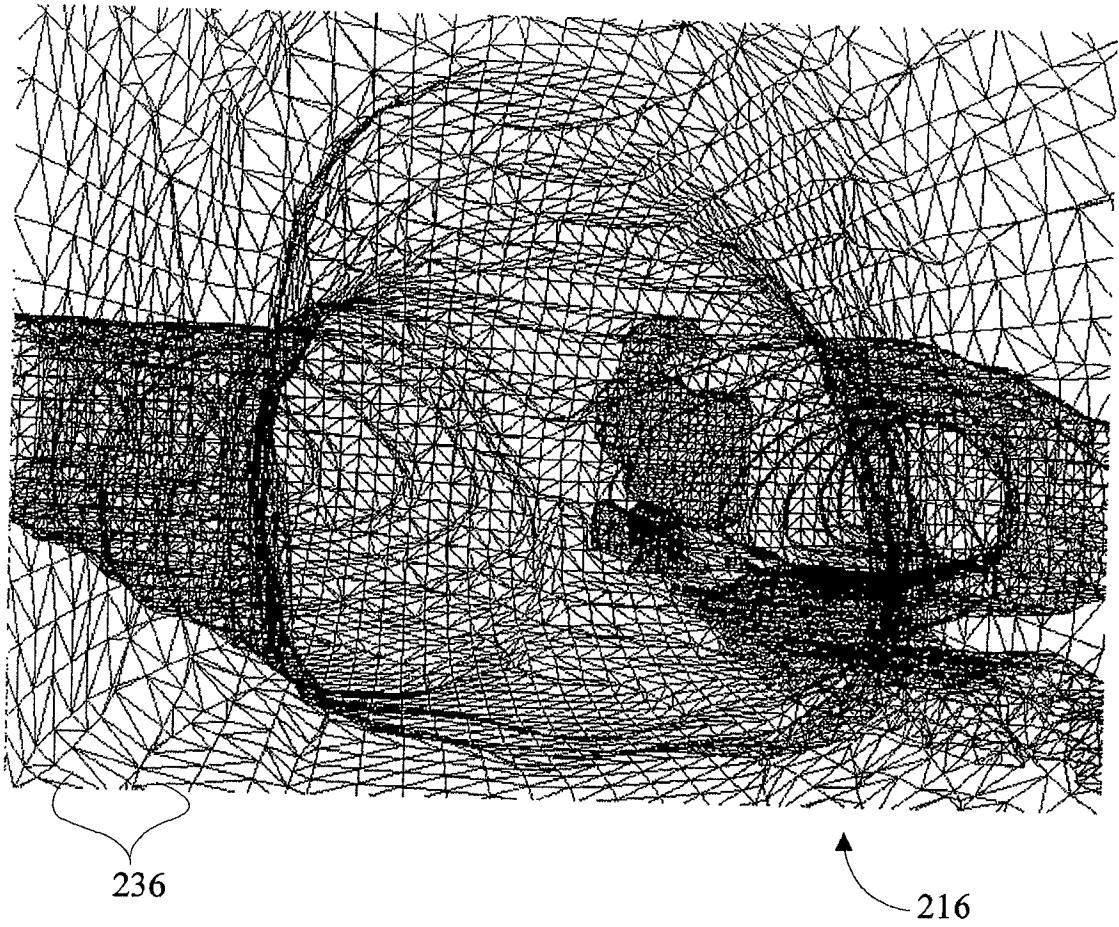
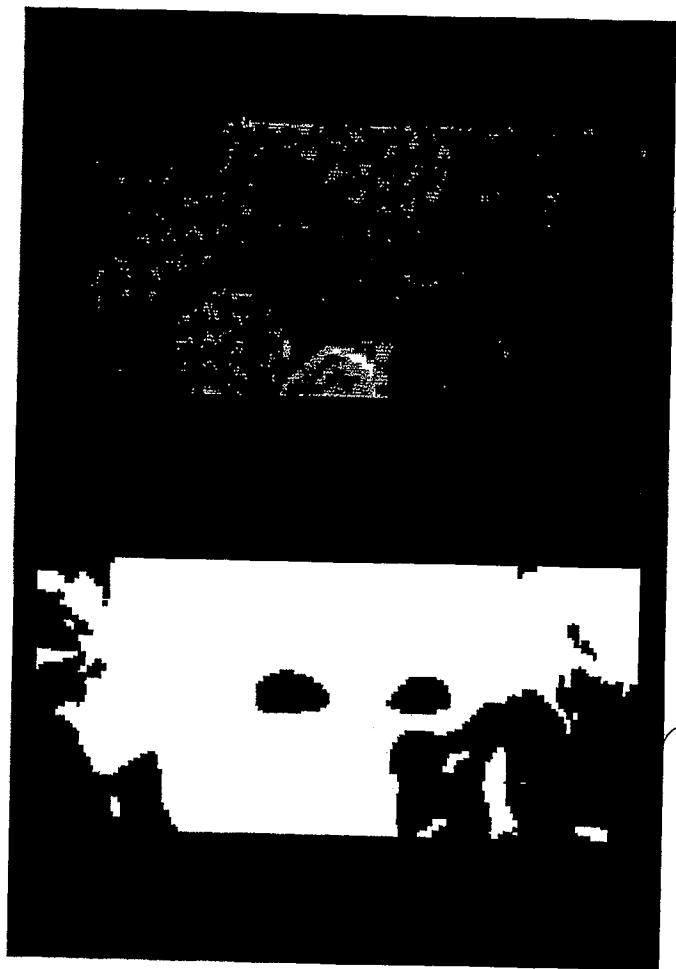


Fig. 17

8
3
8
3



212

215

Fig. 16

BB
225
226
227

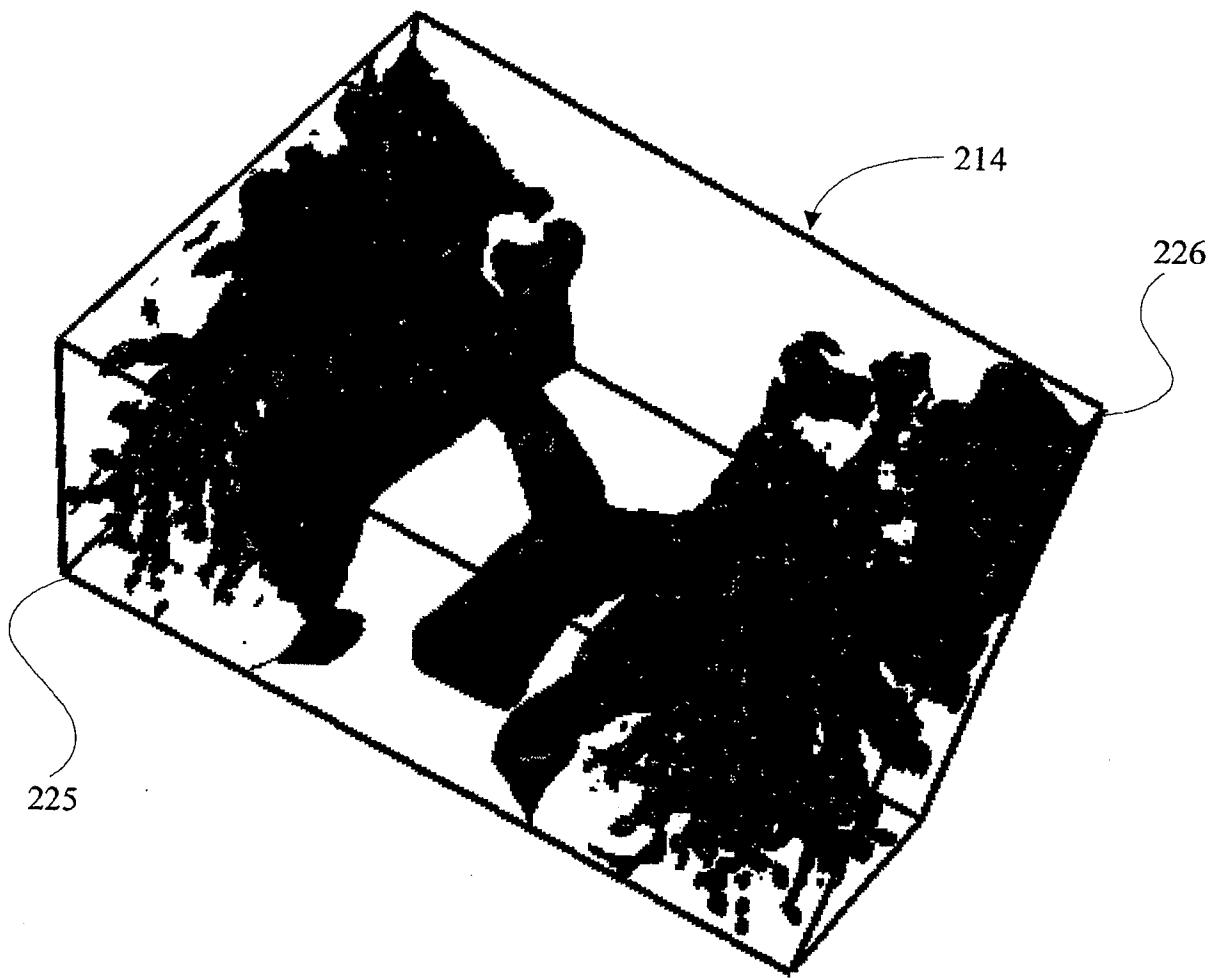
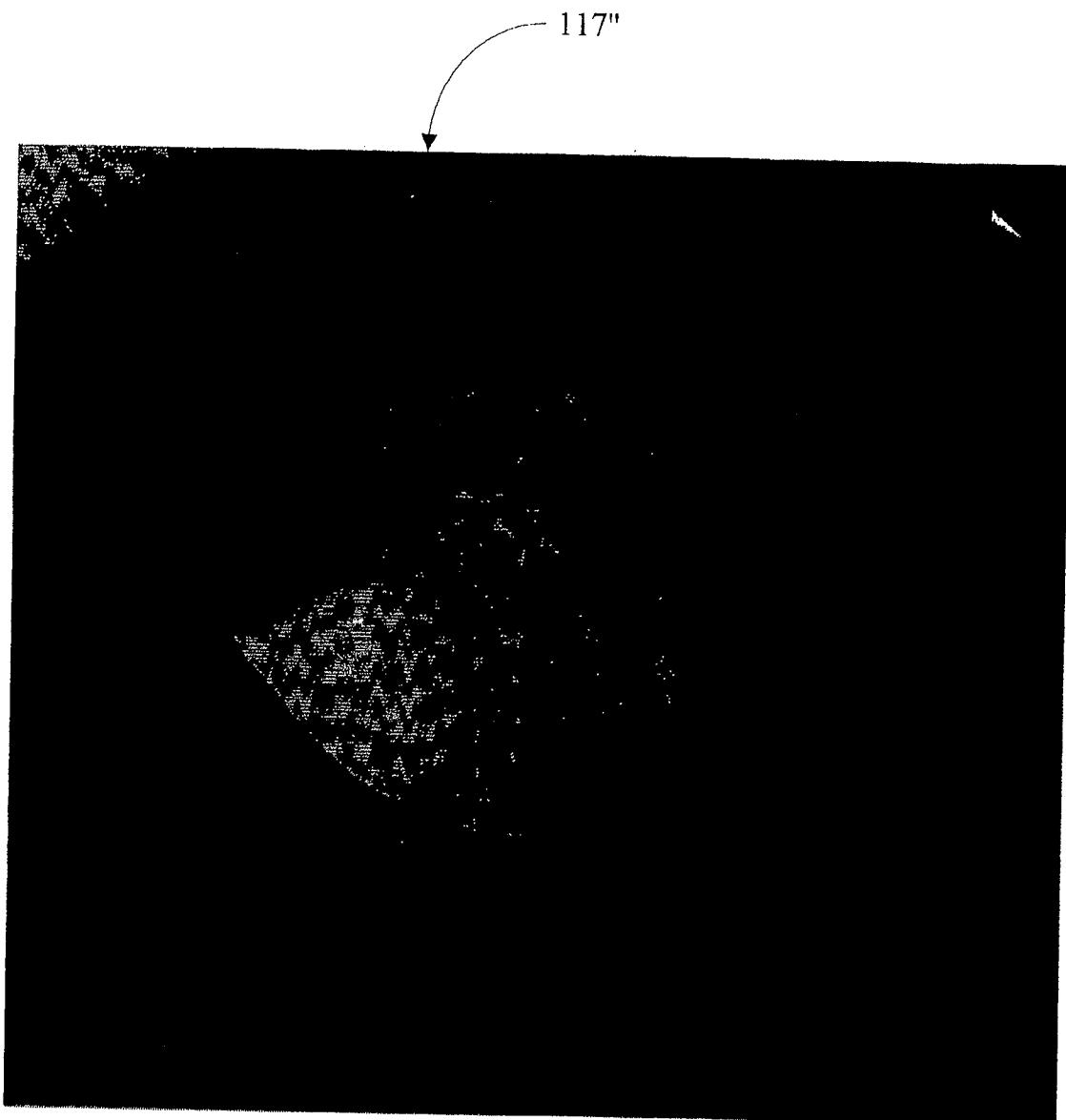


Fig. 15



2
3
+
3
5
8

Fig. 14

13
13
13
13

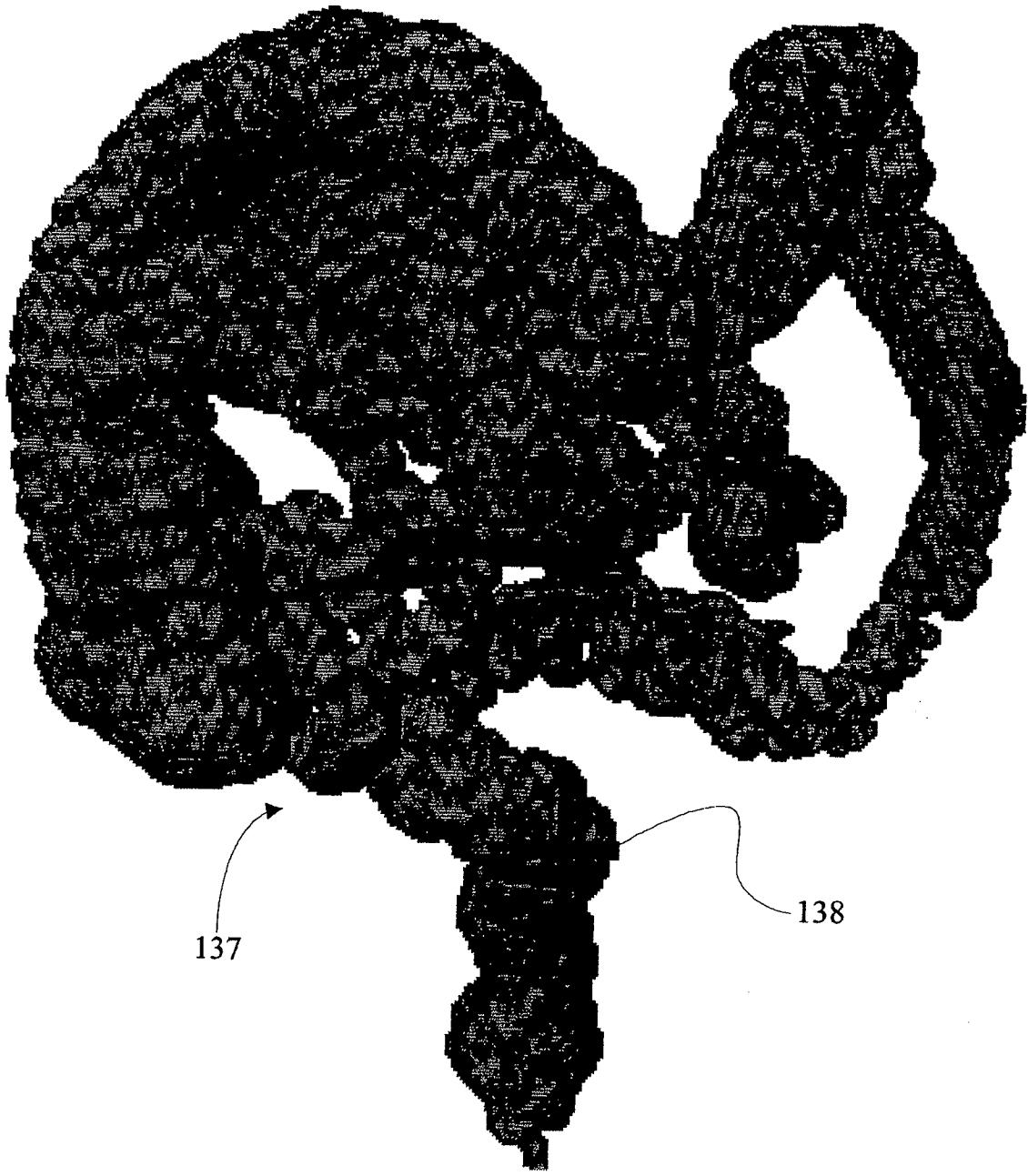


Fig. 13

3
3
3
3

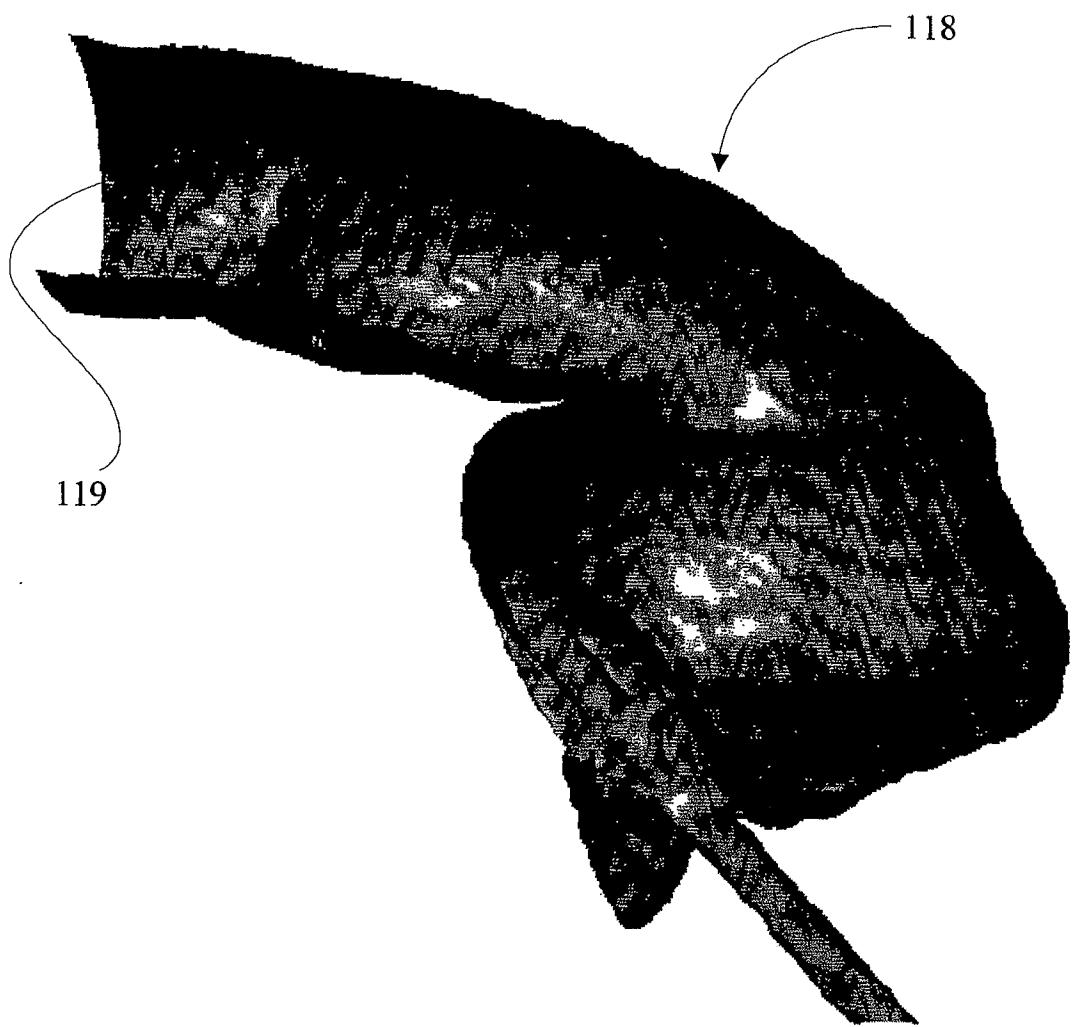


Fig. 12

8
12
3
33
53

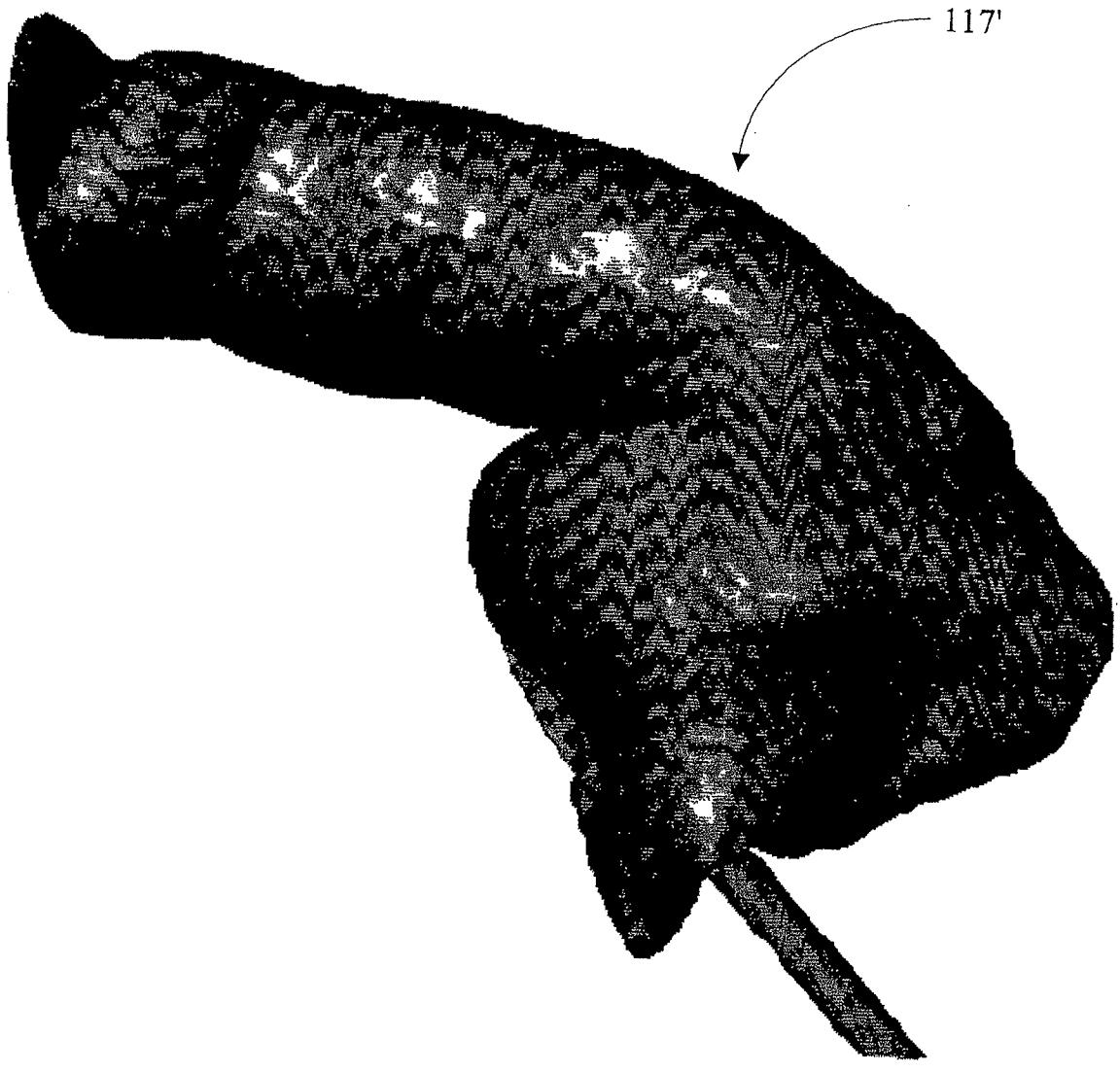


Fig. 11

88
89
90
91
92
93
94

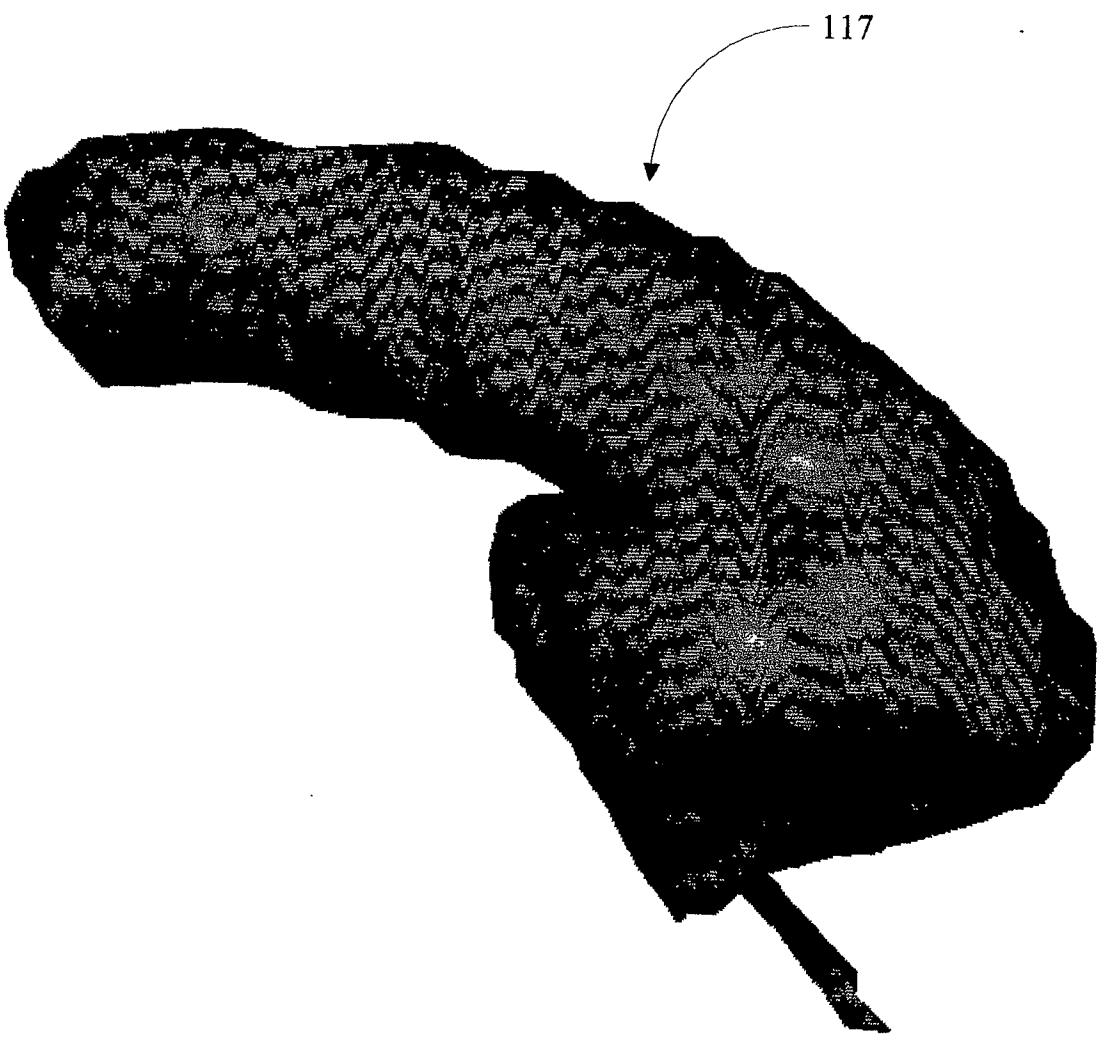


Fig. 10

8
5
3
3
2

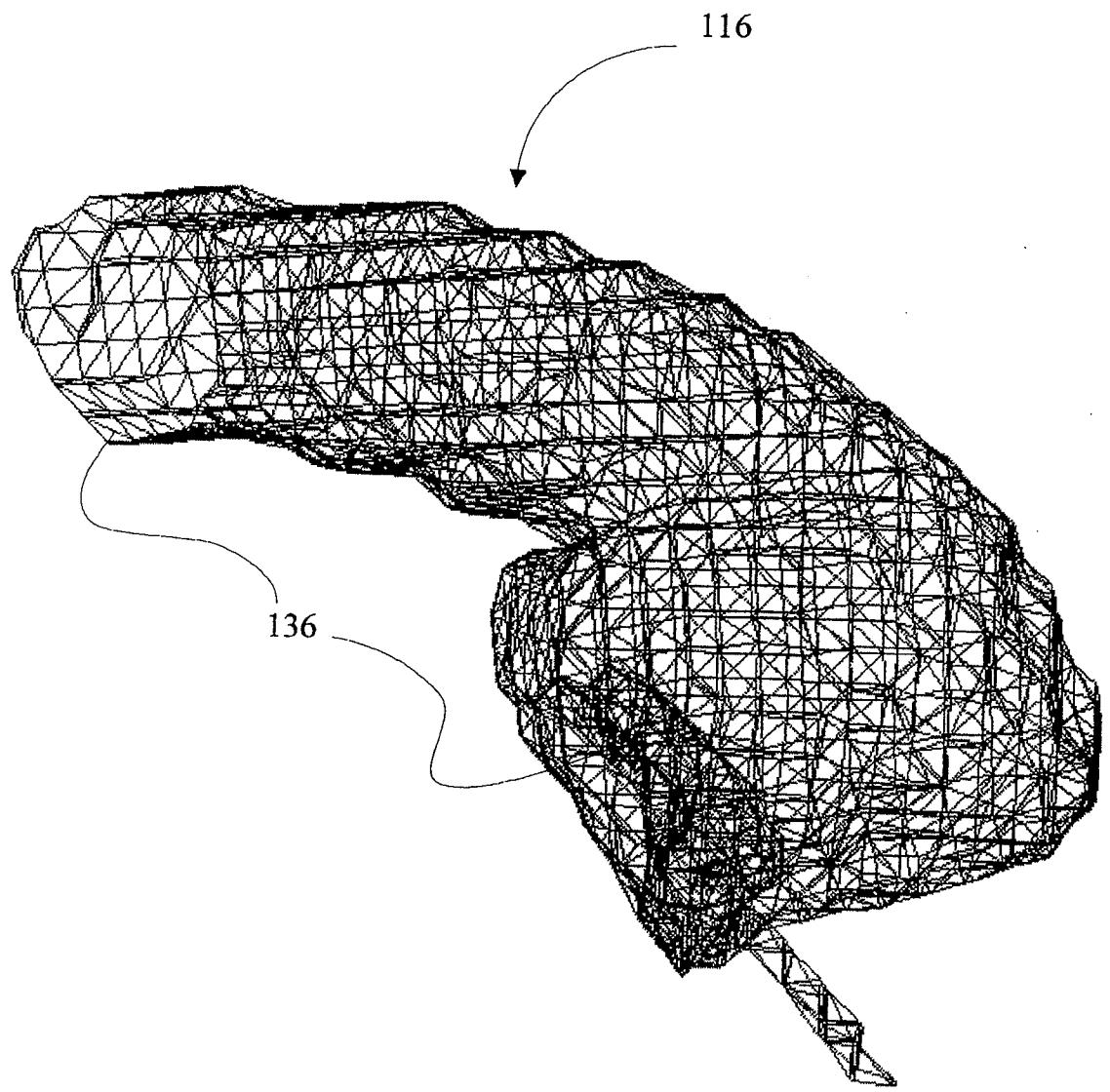


Fig. 9

88
89
89
89

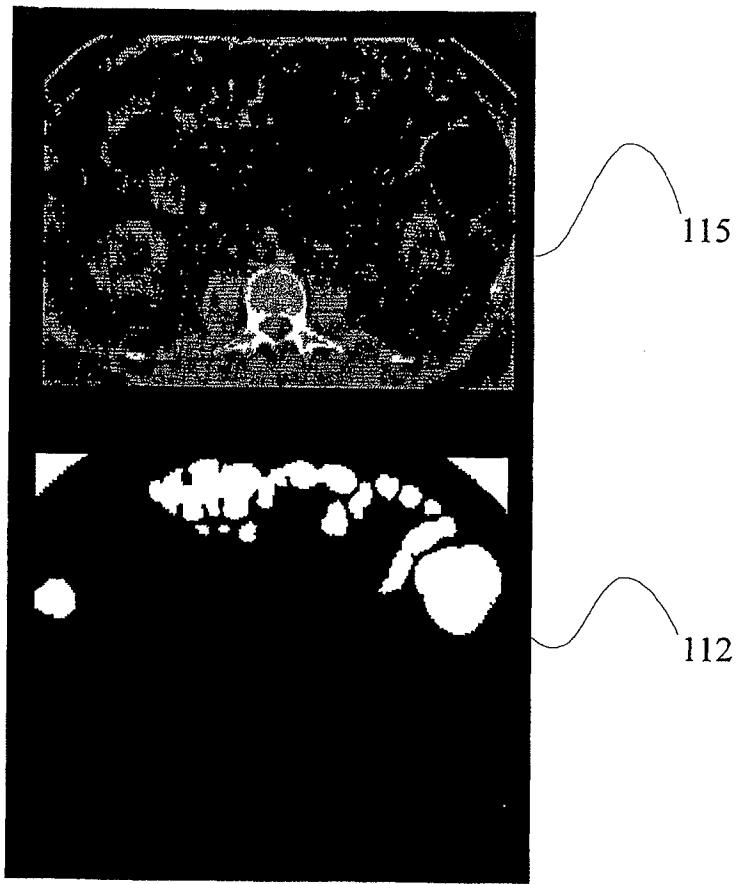


Fig. 8

8
7
3
2

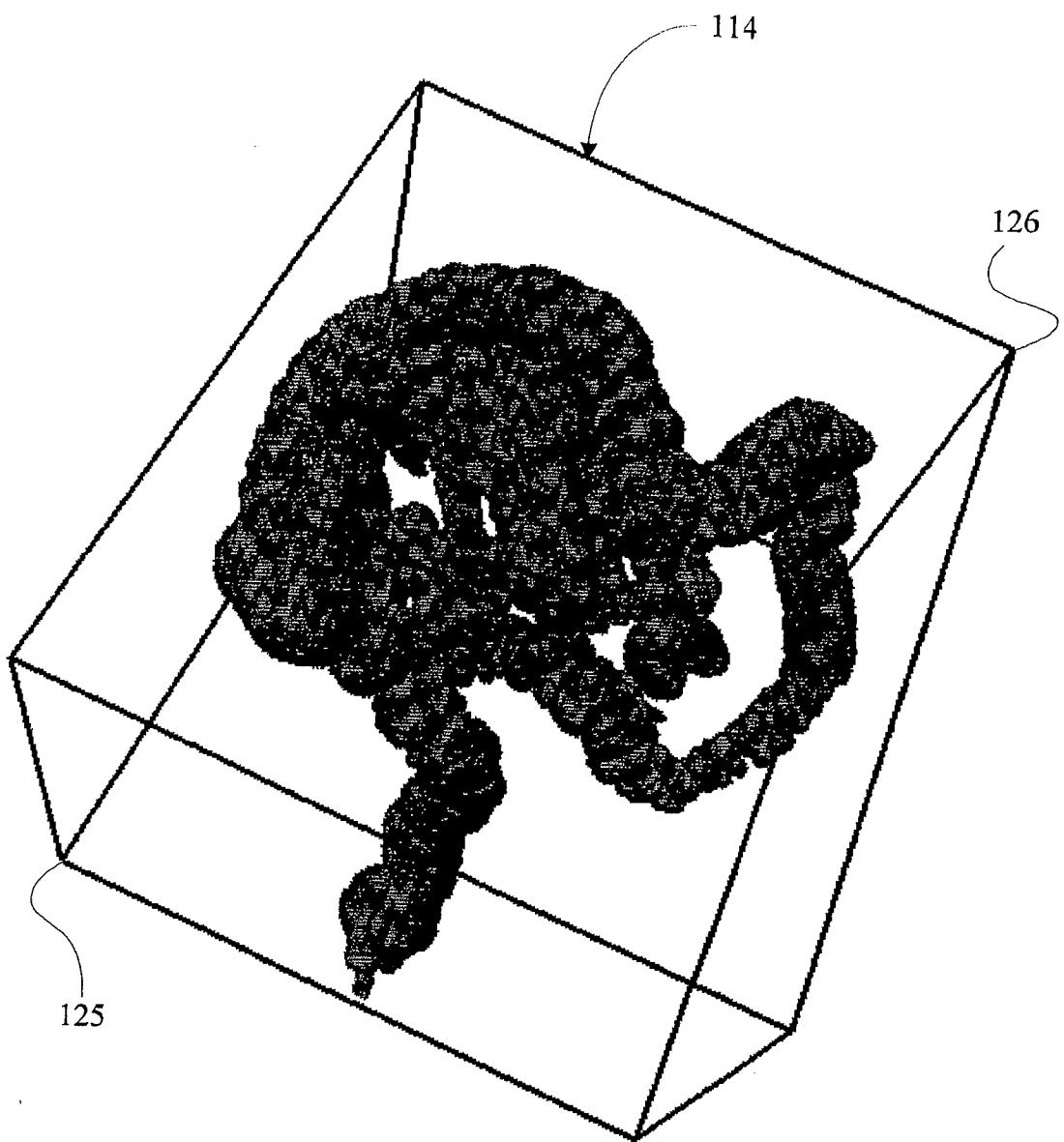


Fig. 7

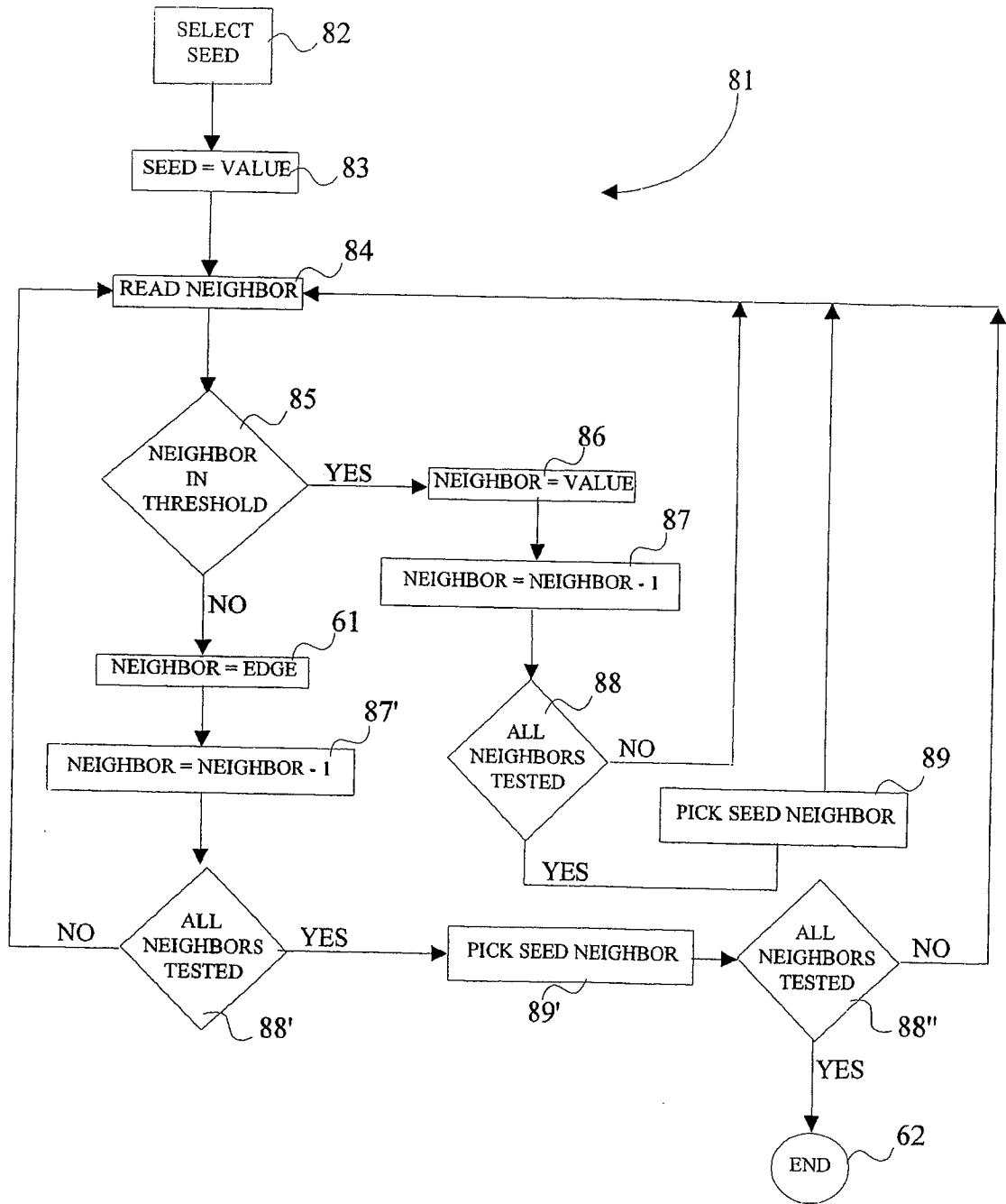


Fig. 6

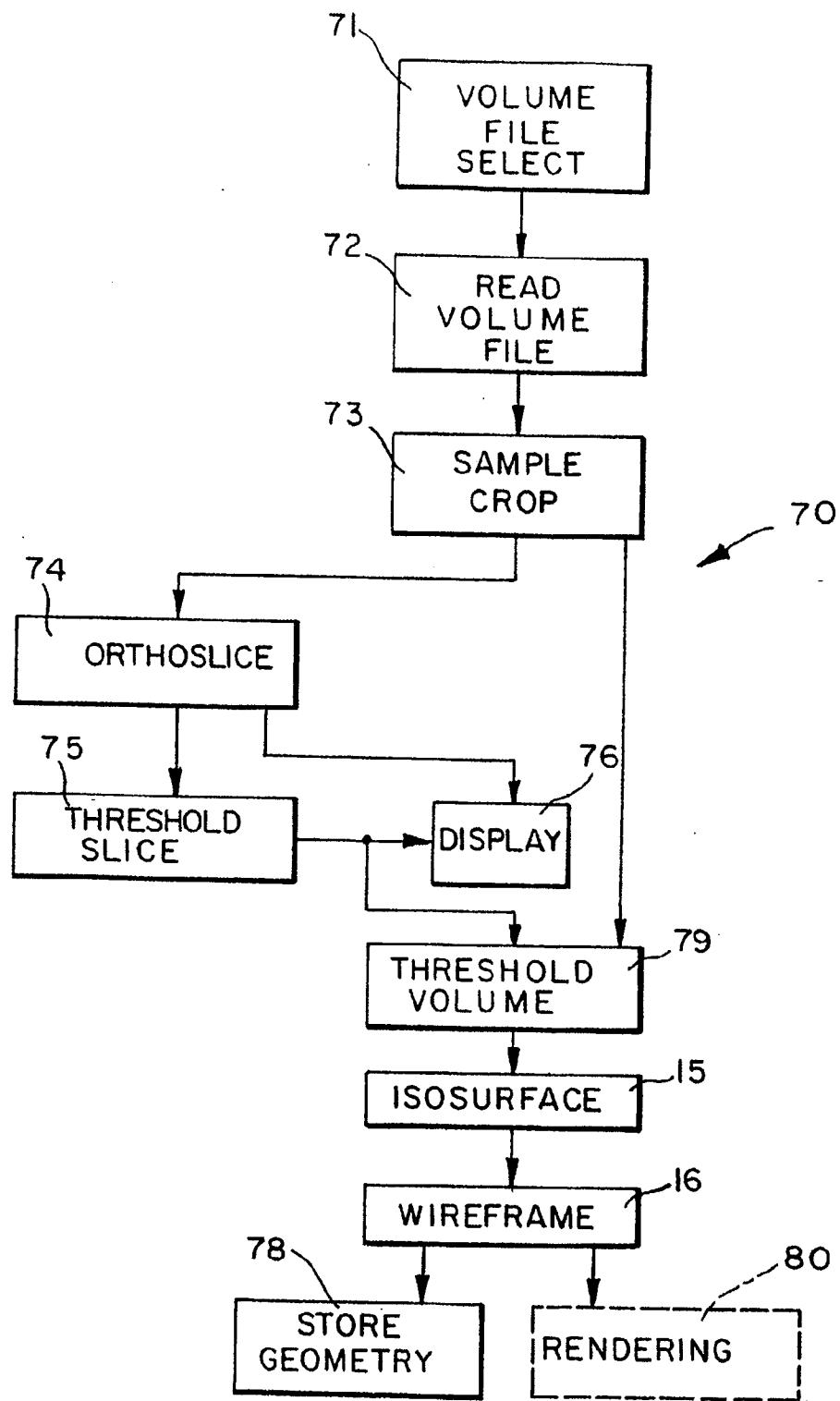
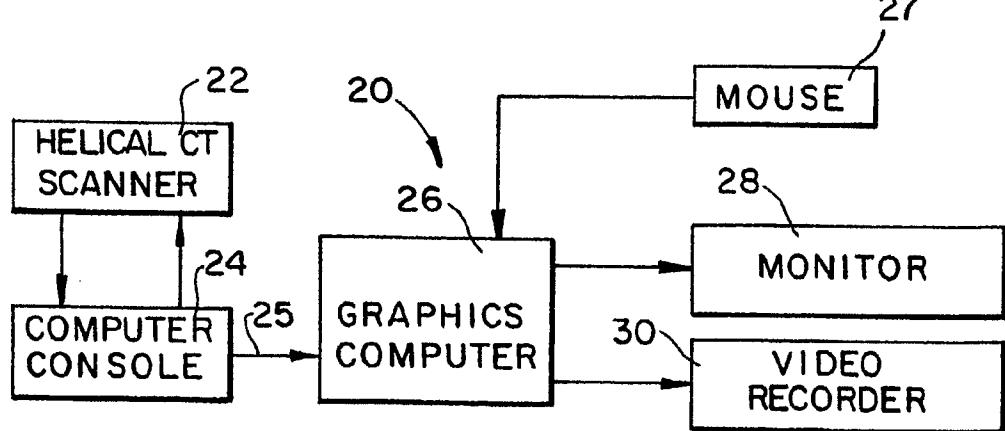
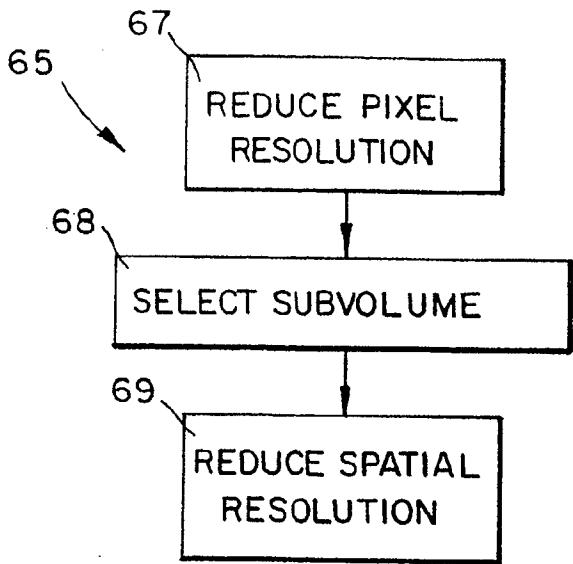
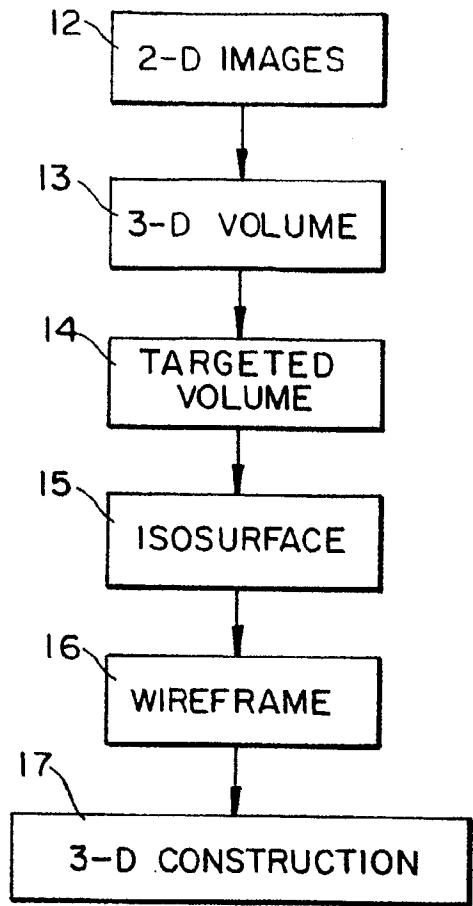


FIG.5



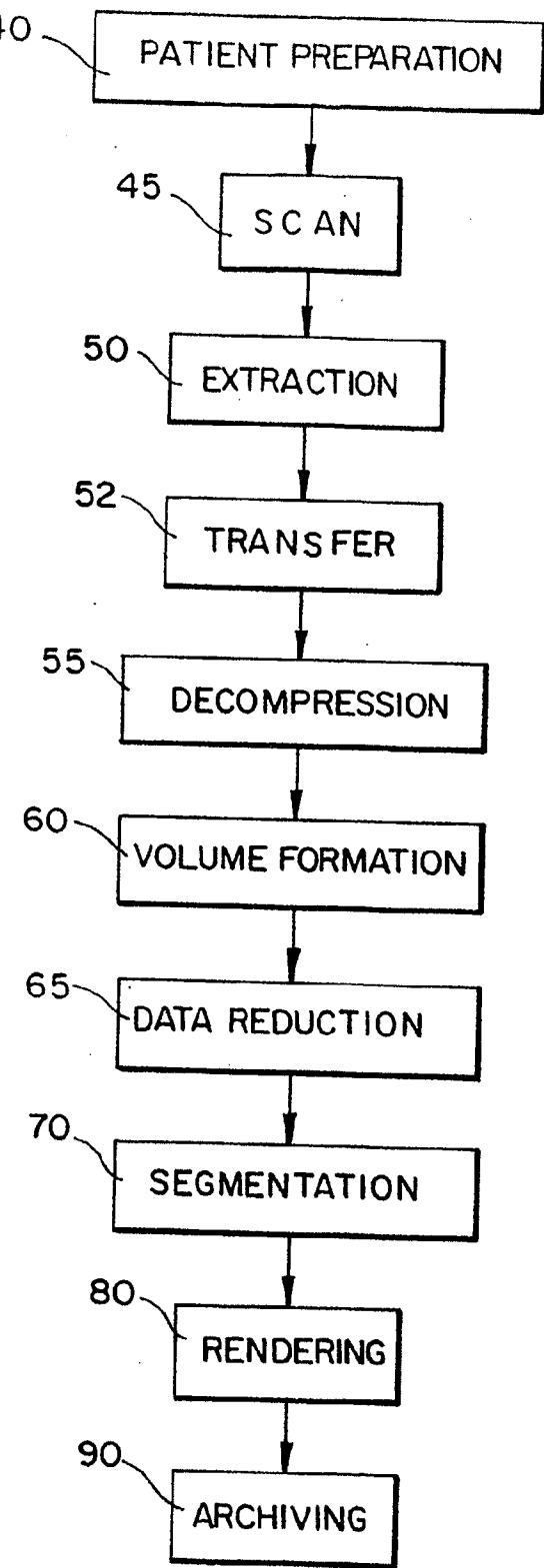


FIG. 1

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drawings.

Dated this 18th day of March, 1998

WAKE FOREST UNIVERSITY

5 By Its Patent Attorneys

DAVIES COLLISON CAVE

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R



display of the segmented region of interest: and

b. transparency means for rendering all portions of the three-dimensional display on one side of the cutting plane transparent.

5 158. The system as recited in claim 156 wherein the splitting means includes center line splitting means for splitting open the three-dimensional display of the segmented region of interest along a line which passes along a center of the three-dimensional display of the segmented region of interest.

10 159. The system as recited in claim 158 wherein the center line splitting means includes:

a. selection means for selecting a seed point which lies within the region of interest;

b. plane determining means for determining a plane of minimum area through the region of interest that passes through the seed point;

15 c. center point determining means for determining the center point of the region of interest that is dissected by the plane of minimum area; and

d. point selecting means for selecting a new point which is spaced from the previous center point in a perpendicular direction relative to the plane of minimum area.

20 160. The system as recited in claim 158 wherein the center line splitting means includes:

a. erosion means for iteratively eroding the region of interest until all of the region of interest disappears, thereby determining the last portions of the region of interest to disappear; and

b. connection means for connecting the last portions of the region of interest to 25 disappear by erosion.

161. A method substantially as hereinbefore described with reference to the accompanying drawings.

30 162. A systems substantially as hereinbefore described with reference to the accompanying



images representing at least one physical property associated with a three dimensional body;

b. segmenting a selected region of interest from the volume of data based on selected values of the physical property representing the selected region of interest, wherein segmenting the region of interest comprises determining the thickness of the region of
5 interest; and

c. rendering the segmented region of interest in a three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.

10 155. The method recited in claim 154 wherein determining the thickness of the region of interest comprises identifying a thickened section of the region of interest by visually differentiating a thickened section on a displayed image from the normal thickness of the region of interest.

15 156. A system for displaying three-dimensional structures comprising:

a. volume formation means for forming a three dimensional volume of data from a series of two dimensional images representing at least one physical property associated with a three-dimensional body;

20 b. segmentation means for segmenting a region of interest from the volume of data based on selected values of the physical property representing the region of interest; and

c. rendering means for rendering the segmented region of interest in a three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment, including splitting means for splitting the three-dimensional display open in selected split open sections therein producing
25 an interactive, cross-sectional, three-dimensional rendering and displaying means for displaying the three-dimensional rendering so that inner surfaces of the split three-dimensional display are visible.

157. The system as recited in claim 156 wherein the splitting means includes:

30 a. plane defining means for defining a cutting plane through the three-dimensional



means comprises an opacity adjusting means for adjusting opacity values.

150. The system as recited in claim 149 wherein the opacity adjustment means comprises means for adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.

151. A system for displaying three-dimensional structures comprising:

a. volume formation means for forming a three dimensional volume of data from a series of two dimensional images representing at least one physical property associated with a three-dimensional body;

b. segmentation means for segmenting a region of interest from the volume of data based on selected values of the physical property representing the region of interest, wherein the segmentation means comprises a means for determining thickness of the region of interest; and

c. rendering means for rendering the segmented region of interest in a three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.

152. The system recited in claim 151 wherein the means for determining thickness of the region of interest comprises a means for displaying a cross-sectional image through the region of interest.

153. The system recited in claim 151 wherein the means for determining thickness of the region of interest comprises means for identifying a thickened section of the region of interest by visually differentiating a thickened section on a displayed image from the normal thickness of the region of interest.

154. A method for displaying three-dimensional structures comprising the steps of:

a. forming a three-dimensional volume of data from a series of two-dimensional



curve representing the number of voxels of a given voxel value as a function of voxel value.

147. A method for interactively displaying a tracheobronchial airway in three dimensions comprising:

- 5 a. an image acquisition step wherein a series of two-dimensional images representing least one physical property associated with the tracheobronchial tree is acquired;
- b. a volume formation step wherein a three-dimensional volume of data is formed by stacking the series of two-dimensional image in computer memory;
- c. a segmentation step wherein a region of interest is segmented from the volume
- 10 of data based on selected values of the physical property representing the region of interest; and
- d. a rendering step wherein the segmented region of interest is rendered in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment, wherein the
- 15 rendering step comprises an opacity adjusting step for adjusting opacity values.

148. The method as recited in claim 147 wherein the opacity adjustment step comprises the step of adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.

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149. A system for interactively displaying three-dimensional structures comprising:

- 25 a. volume formation means for forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body;
- b. segmentation means for segmenting a region of interest from the volume of data based on selected values of the physical property representing the selected region of interest; and
- c. rendering means for rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of
- 30 interest, therein producing a virtual three-dimensional environment, wherein the rendering



143. A method for interactively displaying three-dimensional structures comprising the steps of:

- a. forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body;
- 5 b. segmenting a selected region of interest from the volume of data based on selected values of the physical property representing the selected region of interest; and
- c. rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment, wherein the rendering step comprises an
10 opacity adjusting step for adjusting opacity values.

144. The method as recited in claim 143 wherein the opacity adjustment step comprises the step of adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.

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145. A method for interactively displaying a colon in three dimensions comprising:
- a. an image acquisition step wherein a series of two-dimensional images representing at least one physical property associated with the colon is acquired;
 - b. a volume formation step wherein a three-dimensional volume of data is formed
20 by stacking the series of two-dimensional images in computer memory;
 - c. a segmentation step wherein a region of interest related to the colon is segmented from the volume of data based on selected values of the physical property representing the region of interest; and
 - d. a rendering step wherein the segmented region of interest is rendered in an
25 interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment, wherein the rendering step comprises an opacity adjusting step for adjusting opacity values.

146. The method as recited in claim 145 wherein the opacity adjustment step comprises the
30 step of adjusting the opacity values to the values determined along the inverse of a histogram



138. A system for interactively displaying three-dimensional structures comprising:

a. volume formation means for forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body;

5 b. segmentation means for segmenting a region of interest from the volume of data based on selected values of the physical property representing the selected region of interest, wherein the segmentation means comprises:

i undersegmentation means for under segmenting the region of interest from the volume of data; and

10 ii. morphological dilation means for adding a layer of voxels to the undersegmented region of interest to form a segmented region of interest; and

c. rendering means for rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.

15

139. The system as recited in claim 138 wherein the segmentation means comprises a thresholding mean for determining threshold values corresponding to the selected values of the physical property to isolate the selected region of interest.

20 140. The system as recited in claim 138 wherein the segmentation means comprises a region growing means.

141. The system as recited in claim 138 wherein the morphological dilation means comprises means for adding all voxels in the three-dimensional volume of data that are 25 adjacent to the undersegmented region interest to the undersegmented region of interest.

142. The system as recited in claim 138 wherein the morphological dilation means comprises means for adding a thickness of voxels in the three-dimensional volume of data that are adjacent to the undersegmented region of interest to the undersegmented region of 30 interest.



- a. forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body, wherein the three-dimensional volume of data comprises a three-dimensional matrix of voxels;
- 5 b. segmenting a selected region of interest from the volume of data based on selected values of the physical property representing the selected region of interest, wherein the segmentation step comprises the steps of:
 - i. undersegmenting the selected region of interest from the volume of data; and
 - 10 ii. adding a layer of voxels to the undersegmented region of interest to form a segmented region of interest; and
 - c. rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.
- 15 134. The method as recited in claim 133 wherein the step of segmenting the selected region of interest comprises a thresholding step for determining threshold values corresponding to the selected values of the physical property to isolate the selected region of interest.
- 20 135. The method as recited in claim 133 wherein the step of segmenting the selected region of interest comprises a region growing step.
136. The method as recited in claim 133 wherein the step of adding a layer of voxels to the undersegmented region of interest comprises the step of adding all voxels in the three-dimensional volume of data that are adjacent to the undersegmented region of interest to the
25 undersegmented region of interest.
137. The method as recited in claim 133 wherein the step of adding a layer of voxels to the undersegmented region of interest comprises the step of adding a thickness of voxels in the three-dimensional volume of data that are adjacent to the undersegmented region of
30 interest to the undersegmented region of interest.



voxel value.

126. The system as recited in claim 100 comprising selection means for selecting a point which lies within the segmented region of interest and displaying a two-dimensional image
5 which lies in a plane passing through the selected point.

127. The system as recited in claim 100 comprising assignment means for assigning at least one point of interest along the segmented region of interest rendered in the displayed three-dimensional display.

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128. The system as recited in claim 100 comprising external map means for displaying an external map of the three-dimensional display

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129. The system as recited in claim 100 wherein the rendering means includes transparency means for rendering a portion of the region of interest semi-transparent.

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130. The system as recited in claim 100 wherein the rendering means includes splitting means for splitting the three-dimensional display open in selected split open sections and displaying means for displaying the split open sections so that inner surfaces of the split three-dimensional display are visible.

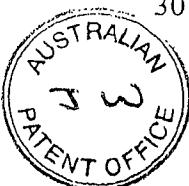
131. The system as recited in claim 100 wherein the rendering means comprises simulation means for simulating movement along a center line through the segmented region of interest of the three-dimensional display.

25

132. The system as recited in claim 100 wherein the step of segmenting the region of interest comprises a region growing step.

133. A method for interactively displaying three-dimensional structures comprising the

30 steps of:



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119. The system as recited in claim 110 wherein the segmentation means comprises a morphological dilation means for adjusting the segmented region of interest.

120. The system as recited in claim 119 wherein the morphological dilation means
5 comprises:

a. undersegmentation means for undersegmenting the region of interest from the volume of data; and

b. layer means for adding a layer of voxels to the undersegmented region of interest to form a segmented region of interest.

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121. The system as recited in claim 120 including means for producing a wireframe model of the isolated region of interest.

122. The system recited in claim 120 wherein the thresholding means comprises:

15 a. a threshold selection means for selecting threshold values; and
b. a threshold adjustment means for adjusting the threshold values.

123. The system as recited in claim 122 wherein the threshold adjustment means comprises:

a. orthoslice means for taking an orthoslice through the region of interest to
20 produce an orthoslice image; and

b. display means for displaying the orthoslice image and a corresponding thresholded images, so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice.

25 124. The system as recited in claim 100 wherein the volume rendering means comprises an opacity adjusting means for adjusting opacity values.

125. The system as recited in claim 124 wherein the opacity adjustment means comprises means for adjusting the opacity values to the values determined along the inverse of a
30 histogram curve representing the number of voxels of a given voxel value as a function of



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113. The system as recited in claim 112 wherein the threshold adjustment means comprises:

- a. orthoslice means for taking an orthoslice through the region of interest to produce an orthoslice image; and
- b. display means for displaying the orthoslice image and a corresponding thresholded image, so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice image.

114. The system as recited in claim 110 wherein the segmentation means comprises a morphological dilation means for adjusting the segmented region of interest.

10

115. The system as recited in claim 114 including means for producing a wireframe model of the isolated region of interest.

116. The system recited in claim 114 wherein the thresholding means comprises:

15

- a. a threshold selection means for selecting threshold values; and
- b. a threshold adjustment means for adjusting the threshold values.

117. The system as recited in claim 116 wherein the threshold adjustment means comprises:

20

- a. orthoslice means for taking an orthoslice through the region of interest to produce an orthoslice image; and

25 b. display means for displaying the orthoslice image and a corresponding thresholded image, so that the threshold values can be adjusted while comparing the thresholded image to the corresponding orthoslice.

118.

The system as recited in claim 114 wherein the morphological dilation means comprises:

- a. undersegmentation means for undersegmenting the region of interest from the volume of data; and
- b. layer means for adding a layer of voxels to the undersegmented region of interest to form a segmented region of interest.

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103. The system as recited in claim 101 wherein the series of two-dimensional images comprises images taken at 1 mm regularly spaced grid locations within the body.

104. The system as recited in claim 101 wherein the series of two-dimensional images
5 comprises computed tomography images.

105. The system as recited in claim 104 wherein the computed tomography images comprise helical computed tomography images.

10 106. The system as recited in claim 100 further comprising reduction means for reducing the size of the volume of data.

15 107. The system as recited in claim 106 wherein the reduction means comprises means for reducing pixel resolution.

108. The system as recited in claim 106 wherein the reduction means comprises means for reducing the spatial resolution.

20 109. The system as recited in claim 106 wherein the reduction means comprises means for creating a sub-volume of data.

110. The system as recited in claim 100 wherein the segmentation means comprises a thresholding means for determining a threshold range used to isolate the region of interest.

25 111. The system as recited in claim 110 including means for producing a wireframe model of the isolated region of interest.

112. The system as recited in claim 110 wherein the thresholding means comprises:

- a. a threshold selection means for selecting the threshold values; and
- 30 b. a threshold adjustment means for adjusting the threshold values.



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96. The method as recited in claim 78 wherein a portion of the tracheobronchial airway is rendered transparent.

97. The method as recited in claim 78 wherein a portion of the tracheobronchial airway
5 is rendered semi-transparent.

98. The method as recited in claim 78 wherein the volume rendering step comprises an opacity adjusting step for adjusting opacity values.

10 99. The method as recited in claim 98 wherein the opacity adjustment step comprises the step of adjusting the opacity values to the values determined along the inverse of a histogram curve representing the number of voxels of a given voxel value as a function of voxel value.

100. A system for interactively displaying three-dimensional structures comprising:

15 a. volume formation means for forming a three-dimensional volume of data from a series of two-dimensional images representing at least one physical property associated with a three-dimensional body;

b. segmentation means for segmenting a region of interest from the volume of data based on selected values of the physical property representing the selected region
20 interest; and

c. rendering means for rendering the segmented region of interest in an interactive three-dimensional display for interaction with internal surfaces of the segmented region of interest, therein producing a virtual three-dimensional environment.

25 101. The system as recited in claim 100 wherein the series of two-dimensional images comprises images taken at regularly spaced grid locations within the body.

102. The system as recited in claim 101 wherein the spacing between successive grid locations is selected to produce isocubic voxels for three-dimensional display.

